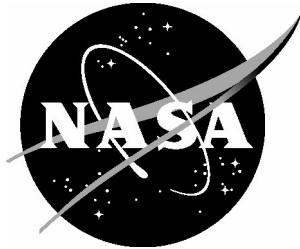


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1998 Calibration of the Mach 4.7 and Mach 6 Arc-Heated Scramjet Test Facility Nozzles

*David W. Witte, Richard G. Irby, Aaron H. Auslender, and Kenneth E. Rock
Langley Research Center, Hampton, Virginia*

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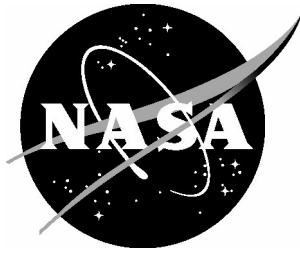
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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Abstract

A calibration of the Arc-Heated Scramjet Test Facility (AHSTF) Mach 4.7 and Mach 6 nozzles was performed in 1998. For each nozzle, three different typical facility operating test points were selected for calibration. Each survey consisted of measurements, at 340 separate locations across the 11 inch square nozzle exit plane, of pitot pressure, static pressure, and total temperature. Measurement density was higher (4/inch) in the boundary layer near the nozzle wall than in the core nozzle flow (1/inch).

The results generated for each of these calibration surveys were contour plots at the nozzle exit plane of the measured and calculated flow properties which completely defined the thermodynamic state of the nozzle exit flow. An area integration of the mass flux at the nozzle exit for each survey was compared to the AHSTF mass flow meter results to provide an indication of the overall quality of the calibration performed. The percent difference between the integrated nozzle exit mass flow and the flow meter ranged from 0.0 to 1.3 percent for the six surveys. Finally, a comparison of this 1998 calibration was made with the 1986 calibration. Differences of less than 10 percent were found within the nozzle core flow while in the boundary layer differences on the order of 20 percent were quite common.

Introduction

Continued interest in the development of hypersonic airbreathing propulsive systems, such as airframe-integrated scramjet vehicles for the Hyper-X program (ref. 1.) requires both maintenance and improvements of the few ground test facilities within the United States which are capable of conducting this type of research. One such facility is the Arc-Heated Scramjet Test Facility (AHSTF) at NASA Langley Research Center in Hampton, Virginia. In an effort to better define the flow quality produced by the AHSTF, a calibration of the nozzle exit flow was conducted in 1998 for both the Mach 4.7 and Mach 6.0 facility nozzles. This calibration was an attempt to improve upon the previous AHSTF calibration conducted in 1986 (ref 2.) The 1998 calibration utilized a much more extensive set of survey locations than was utilized in 1986. The 1998 calibration also utilized survey probes that were designed to be tested at the full enthalpy test conditions so that enthalpy scaling from a calibration test point to a typical facility test point would not have to be performed, as was the case for the 1986 calibration.

A critical first step for any scramjet ground test program is to thoroughly understand the nozzle exit flowfield for the test facility. This can only be accomplished by a measured calibration of the flow exiting the facility nozzle. The accuracy of the propulsive performance results from an engine test will be directly dependent on the knowledge of the spatial and temporal uniformity of the nozzle exit flow. Therefore, the quality of any engine test results will be no better than the quality of the nozzle exit flow calibration for that facility. This

connection between the quality of the engine test data and the facility nozzle calibration led to a desire to acquire a higher quality AHSTF calibration in 1998.

Nomenclature

AHSTF	Arc-Heated Scramjet Test Facility
CFD	computational fluid dynamic
Core	nozzle core flow (a 5 by 5 inch square)
exp	experimental
F	stream thrust (lb_f/ft^2)
HAPB	Hypersonic Airbreathing Propulsion Branch
H_s	static enthalpy (btu/lb_m)
HST	sonic throat enthalpy (btu/lb_m)
H_{t1}	freestream total enthalpy (btu/lb_m)
P_s	static pressure (psia)
Pt	platinum
P_{t2}	pitot pressure (psia)
PT1	facility plenum pressure (psia)
Rh	rhodium
S	entropy ($\text{btu}/\text{lb}_m^\circ\text{R}$)
T_s	static temperature ($^\circ\text{R}$)
TT1	facility total temperature ($^\circ\text{R}$)
T_{t2}	total temperature ($^\circ\text{R}$)
V	velocity (ft/s)

W	facility mass flow (lb _m /s)
1	flow state just upstream of probe bow shock
1s	stagnation condition of 1
2	flow state just downstream of probe bow shock
2s	stagnation condition of 2
ρ	static density (lb _m /ft ³)

Test Facility

A photograph of the AHSTF is shown in figure 1 and a schematic of the tunnel circuit is provided in figure 2. The facility is described in detail in references 3 and 4. The primary purpose of the facility is to provide an air gas test flow with true velocity, static temperature, and static pressure over a simulated flight Mach number range from 4.7 to 8, so that the performance of scramjet powered vehicles may be assessed.

A longitudinal section view of the electric arc heater and the plenum chamber is shown in Figure 3. The arc is established between the electrodes and, except for the termination regions, is confined along the heater centerline by the vortex flow of the main air stream, which is purposely injected with a tangential velocity (swirled in). The arc-heated air (total temperature approximately 8500 degrees R) is mixed in the plenum chamber with an unheated bypass air stream to form a resultant test stream with the desired stagnation conditions. The resulting plenum total temperature can range from 1000 to 5200 degrees R with the total pressure ranging up to 660 psia. The bypass air is injected radially from the plenum rings. This radial injection enhances mixing and also helps to break up the swirl downstream of the arc heater to improve flow quality for engine testing. This heated air is expanded through a contoured nozzle into a circular open jet test section roughly 4 feet in diameter and 10 feet in length. The flow is then diffused to subsonic velocity, cooled by an aftercooler, and exhausted into a vacuum sphere

Two separate facility nozzles provide exit Mach number flows of 4.7 and 6.0. A schematic for each of these nozzles is give in figure 4. Both of these nozzles possess square cross sections and water cooled copper throats with uncooled steel expansion sections. Each

nozzle provides a nominal 11 X 11 inch exit flowfield.

Calibration Instrumentation

Three types of flow measurements, pitot pressure, static pressure, and total temperature, were obtained at the plane of the nozzle exit for both the Mach 4.7 and Mach 6.0 AHSTF nozzles. These three measurements, along with knowledge of the nozzle exit plane gas composition (ref 5.), were sufficient information to fully define the state of the flow at the nozzle exit. A photograph of the measurement probes designed and fabricated for this calibration effort is shown in Figure 5. This photograph shows the probes installed in their respective rake mounts. This photograph also shows the separate boundary layer rakes used for measurement of the pitot pressure and total temperature in the boundary layer.

Figure 6 provides a schematic showing the material design and geometric details for each of the five individual types of measurement probes. In the core flow at the nozzle exit plane, one inch spacing between the measurement probes was deemed sufficient for spatial resolution of the nozzle exit flow. With this spacing, it was possible to design large enough pitot and static pressure probes made from stainless steel which would survive the thermal heat load resulting from a typical 20 second tunnel run. In the boundary layer, less thick pitot probes were used to enable 0.25 inch spatial resolution. These boundary layer pitot probes were able to also thermally survive even though they represented a much smaller heat sink source because of the reduced heat loads in the boundary layer. The boundary layer and core flow total temperature probes possessed 0.25 and 1.0 inch spacing respectively, same as the spacing for the pressure probes. The boundary layer total temperature probe was essentially a geometrically scaled version of the core flow total temperature probe. These temperature probes were fabricated with a Pt/30%Rh outer shield which could withstand the 3800 degree R stagnation temperature at the highest enthalpy test point. Type B thermocouple wire was utilized in these probes to enable measurement of this level of temperature.

Figure 7 shows the three core flow rakes and the eight boundary layer rakes (four pitot and four total temperature) installed at the nozzle exit plane for one of the ten tunnel runs necessary to conduct a complete calibration survey of the nozzle exit flowfield. This is a view

from the nozzle throat looking downstream. The reflection of the flow rakes on the nozzle sidewall can be seen in the left hand side of the photograph. The minimum spacing between the centerline of the core flow rakes for any given run was at least 2.0 inches. This prevented the bow shock from either the pitot pressure or total temperature probes from affecting the measurement of static pressure 2.81 inches downstream from the static pressure probe tip. The minimum spacing between the boundary layer probe rakes was 1.0 inch. Figure 8 shows the rear view of the calibration probes installed at the nozzle exit for the same tunnel run.

Calibration Surveys

For this 1998 AHSTF calibration of the Mach 4.7 and Mach 6 nozzles, three typical facility operating test points were surveyed for each nozzle. Table 1 provides the facility plenum pressure (PT1), sonic throat enthalpy (HST), total temperature (TT1), and mass flow (W) for each of these calibration test points. Figure 9 shows the number and location of individual probe measurements acquired at the facility nozzle exit plane for each of the six test conditions. Each calibration survey is a result of pitot pressure, static pressure, and total temperature measurements obtained at 340 locations across the nozzle exit plane from ten separate tunnel runs. The higher density of measurements in the boundary layer is clearly evident in Figure 9. To accomplish each survey in just ten tunnel runs a specific set of rake position moves was utilized. Table 2 documents this specific set of rake position moves in the form of a test matrix for the AHSTF Mach 6 nozzle calibration. The same set of rake position moves was also utilized for the Mach 4.7 nozzle calibration.

Data Analysis Methodology

A set of data reduction computations performed on each data set is listed in Table 3. After the required ten tunnel runs were made, the ten data files from each run were assimilated by a computer code into a single file yielding a set of pitot pressure, static pressure, and total temperature measurements corresponding to the survey locations of figure 9. This set of data measurements was then interpolated onto the 0.25 inch spatial resolution, uniform, rectangular grid with 2025 interpolated data locations as shown in figure 10 using Tecplot's linear interpolation feature (ref 6.).

With the full set of measured interpolated pitot pressure, static pressure, and total temperature data, the complete thermodynamic state of the flow was determined at every interpolated survey location in the nozzle exit plane. Table 4 lists the individual calculation steps involved in this process. Step 1 yields the value of total enthalpy, H_{t1} . H_{t1} is considered a quasi-measured flow property because the total temperature probes essentially double as total enthalpy probes. The total enthalpy distribution at the nozzle exit plane is assumed to be similar to the total temperature distribution. This assumption, along with the measured value of sonic throat enthalpy, HST, for the facility nozzle enabled the determination of H_{t1} . Steps 2 – 10 were accomplished using the Langley HAPB thermodeck (ref 7.). The physical location of the states 1, 2, and 2s noted in table 4 are shown in figure 11. State 1 is just upstream of the probe bow shock, while state 2 is just downstream of the probe bow shock, and state 2s represents the flow stagnation point at the probe tip. The air test gas at the nozzle exit is considered to be thermodynamically vibrationally frozen. Therefore, steps 2 through 7 were computed with the gas vibrationally frozen. An equivalent set of vibrationally relaxed flow properties was then compute in steps 9 and 10 while conserving the flux quantities of mass, momentum, and energy. This set of vibrationally relaxed flow properties was generated for use with CFD applications in the AHSTF. Most AHSTF CFD applications typically use the nozzle exit flow to initialize their CFD test case. At the present time, most CFD codes cannot account for a vibrationally frozen gas and, therefore, the need for a flux equivalent set of vibrationally relaxed flow properties.

Results

The results of this 1998 AHSTF calibration of the Mach 4.7 and Mach 6 nozzles are presented in the form of contour plots at the nozzle exit plane for individual flow properties. The contour plots for the Mach 4.7 nozzle calibration are presented in figures 12, 13, and 14 for the Mach 5 enthalpy, the Mach 5.5 enthalpy, and the Mach 5 delta PT1 enthalpy test points, respectively. Figures 15, 16, and 17 present the contour plots for the Mach 5 enthalpy, the Mach 6 enthalpy, and the Mach 7 enthalpy test points, respectively, for the Mach 6 nozzle calibration. Each of the figures 12 – 17 is comprised of 22 separate contour plots (a – v). For each, plots a – d are the measured results,

plots e – l are the vibrationally frozen calculated results, and plots m – v are the vibrationally relaxed calculated results. The actual tabulated data files containing all of this flow property information versus the X and Y coordinate positions is available in electronic form on a compact disk that resides with the Langley AHSTF facility resume.

To provide an indication of the overall accuracy of this 1998 calibration, a comparison of the nozzle exit mass flow computed from the measured calibration data was made to the AHSTF mass flow meter result. For each of the six nozzle survey conditions, the computed mass flux values from all 2025 interpolated locations (contour plot l from figures 12 – 17) were area integrated to yield the nozzle exit mass flow. The results of this area integration along with a comparison to the AHSTF mass flow meter results are given in table 5. The percent difference for the six calibration test points ranged from 0.0 to 1.3 percent. These small differences for six separate calibration surveys indicates quality of the calibration technique, the data acquired, and the subsequent data analysis necessary to compute mass flux.

For reference, a comparison of this 1998 AHSTF nozzle calibration was made with the 1986 AHSTF nozzle calibration. A comparison of measured flow properties was made for the Mach 6 nozzle at the Mach 7 enthalpy test condition. Figures 18a, 18c, and 18e present contour plots of pitot pressure, static pressure, and total temperature, respectively, from this 1986 AHSTF calibration. Noted in these contour plots is a striking amount of symmetry which is a result of measured data in one quadrant being mirrored to the other three quadrants. The 1986 calibration, as described in reference 2, consisted of only 66 survey locations, mostly on one half of the nozzle, resulting in the need for the symmetry assumption. With only 66 survey locations (versus 340 for the 1998 calibration), with assumed symmetry, and employing enthalpy scaling because of testing at low enthalpies to acquire static pressure measurements, some differences are to be expected between the 1986 and 1998 AHSTF calibration results. These differences for the measured flow properties are presented in figures 18b, 18d, and 18f in terms of percent difference contour plots. Most of the core flow area of the nozzle exit plane shows differences of less than 10 percent for all three measured flow properties. Only in the boundary layer (less than two inches

from the nozzle walls) does there exist differences of greater than 10 percent. This is most likely a simple result of inadequate probe density in this region for the 1986 calibration.

Summary

In 1998 a calibration of the AHSTF Mach 4.7 and Mach 6 nozzles was performed. For each nozzle, three different typical facility operating test points were selected for calibration, resulting in a total of six calibration surveys. Each survey consisted of measurements of pitot pressure, static pressure, and total temperature at 340 separate locations across the nozzle exit plane. Measurement density was higher (4/inch) in the boundary layer near the nozzle wall than in the core nozzle flow (1/inch).

The results generated for each of these calibration surveys were contour plots at the nozzle exit plane of the measured flow properties, the vibrationally frozen calculated flow properties, and the vibrationally relaxed flow properties. An area integration of the mass flux at the nozzle exit for each survey was compared to the AHSTF mass flow meter results to provide an indication of the overall quality of the calibration performed. The percent difference between the integrated nozzle exit mass flow and the flow meter ranged from 0.0 to 1.3 percent for the six surveys. Lastly, a comparison of this 1998 calibration was made with the 1986 calibration. Differences of less than 10 percent were found within the nozzle core flow while in the boundary layer differences on the order of 20 percent were quite common. These greater differences were likely the result of the significantly lower probe measurement density associated with the 1986 calibration which translated into inadequate definition of the nozzle exit boundary layer flow.

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Facility Nozzle	Flight Enthalpy	PT1 (psia)	HST (btu/lb _m)	TT1 (°R)	W (lb _m /s)
Mach 6	Mach 7	410	1040	3760	4.45
Mach 6	Mach 6	495	795	2915	6.10
Mach 6	Mach 5	400	650	2460	5.41
Mach 4.7	Mach 5	212	573	2185	11.16
Mach 4.7	Mach 5.5	180	690	2600	8.72
Mach 4.7	Mach 5 (ΔP_{t1})	178	580	220	9.30

Table 1. Test conditions for the 1998 AHSTF calibration

				Mounting Location of the 3 Flowfield and 8 Boundary Layer Rakes										
Run Batch	Matrix Run #	Test Enthalpy	Rake ID Position	Ps Rake	Pt2 Rake	Tt Rake	BL Pt2 Rake A	BL Tt Rake A	BL Pt2 Rake B	BL Tt Rake B	BL Pt2 Rake C	BL Tt Rake C	BL Pt2 Rake D	BL Tt Rake D
110.1	1	Mach 5 H	1	B1	B3	B5	C1	C2	C3	C4	C5	C6	C7	C8
110.2	2	Mach 6 H	1	B1	B3	B5	C1	C2	C3	C4	C5	C6	C7	C8
110.3	3	Mach 7 H	1	B1	B3	B5	C1	C2	C3	C4	C5	C6	C7	C8
105.1	4	Mach 5 H	2	B2	B4	B6	C2	C1	C4	C3	C6	C5	C8	C7
105.2	5	Mach 6 H	2	B2	B4	B6	C2	C1	C4	C3	C6	C5	C8	C7
105.3	6	Mach 7 H	2	B2	B4	B6	C2	C1	C4	C3	C6	C5	C8	C7
109.1	7	Mach 5 H	3	B3	B5	B7	S1	S2	S3	S4	S9	S10	C9	C10
109.2	8	Mach 6 H	3	B3	B5	B7	S1	S2	S3	S4	S9	S10	C9	C10
109.3	9	Mach 7 H	3	B3	B5	B7	S1	S2	S3	S4	S9	S10	C9	C10
108.1	10	Mach 5 H	4	B4	B6	B8	S2	S1	S4	S3	S10	S9	C10	C9
108.2	11	Mach 6 H	4	B4	B6	B8	S2	S1	S4	S3	S10	S9	C10	C9
108.3	12	Mach 7 H	4	B4	B6	B8	S2	S1	S4	S3	S10	S9	C10	C9
107.1	13	Mach 5 H	5	B5	B7	B9	B1	B2	S5	S6	S7	S8	T1	T2
107.2	14	Mach 6 H	5	B5	B7	B9	B1	B2	S5	S6	S7	S8	T1	T2
107.3	15	Mach 7 H	5	B5	B7	B9	B1	B2	S5	S6	S7	S8	T1	T2
106.1	16	Mach 5 H	6	B6	B8	B10	B2	B1	S6	S5	S8	S7	T2	T1
106.2	17	Mach 6 H	6	B6	B8	B10	B2	B1	S6	S5	S8	S7	T2	T1
106.3	18	Mach 7 H	6	B6	B8	B10	B2	B1	S6	S5	S8	S7	T2	T1
111.1	19	Mach 5 H	7	B7	B9	B1	B3	B4	B5	B6	B10	T10	T3	T4
111.2	20	Mach 6 H	7	B7	B9	B1	B3	B4	B5	B6	B10	T10	T3	T4
111.3	21	Mach 7 H	7	B7	B9	B1	B3	B4	B5	B6	B10	T10	T3	T4
112.1	22	Mach 5 H	8	B8	B10	B2	B4	B3	B6	B5	B9	T9	T4	T3
112.2	23	Mach 6 H	8	B8	B10	B2	B4	B3	B6	B5	B9	T9	T4	T3
112.3	24	Mach 7 H	8	B8	B10	B2	B4	B3	B6	B5	B9	T9	T4	T3
113.1	25	Mach 5 H	9	B9	B1	B3	B7	B8	T5	T6	T10	B10	T7	T8
113.2	26	Mach 6 H	9	B9	B1	B3	B7	B8	T5	T6	T10	B10	T7	T8
113.3	27	Mach 7 H	9	B9	B1	B3	B7	B8	T5	T6	T10	B10	T7	T8
114.1	28	Mach 5 H	10	B10	B2	B4	B8	B7	T6	T5	T9	B9	T8	T7
114.2	29	Mach 6 H	10	B10	B2	B4	B8	B7	T6	T5	T9	B9	T8	T7
114.3	30	Mach 7 H	10	B10	B2	B4	B8	B7	T6	T5	T9	B9	T8	T7

Table 2. AHSTF Mach 6 nozzle calibration test matrix

Step #	Step Description
1	Average last 20 cycles (last 10 seconds) of run data. This is the best settled static pressure data.
2	Account for run-to-run variation of tunnel conditions by normalization of the run data with Pt nominal and HST nominal.
3	Correct the static pressure data using the static pressure probe recovery factor of 0.96 (based on CFD)
4	<p>Determine the total temperature probe recovery factor for each nozzle calibration test point as shown below:</p> $T_{t2,core} \xrightarrow{\text{NASA Thermochemical Tables}} H_t \xrightarrow{H_t/HST} R_{Tt}$ <p>(Note: R_{Tt} includes stream recovery, conduction and radiation losses, and vibrationally frozen effects.)</p>

Table 3. Experimental data reductions computations

Step #	Step Description
1	calculate H_{t1} : $H_{t1} = \text{HST} (T_{t2, \text{exp}}/T_{t2, \text{exp, core}})$
2	calculate thermodynamic state at 2s: $P_{t2, \text{exp}}, H_{t2} = H_{t1}$ vib froz PH call $\text{=====} \rightarrow S_{t2}$
3	calculate fluid dynamic state at 2: $H_{t2}, S_{t2} = S_2, M2$ (init guess), A vib froz HSMA call $\text{=====} \rightarrow W$
4	calculate fluid dynamic state at 1: $H_{t1} = H_{t2}, P_{t1, \text{exp}}, W, A$ vib froz HPWA call $\text{=====} \rightarrow F_1$
5	calculate fluid dynamic state at 2: $H_{t1}, F_1 = F_2, W, A$ vib froz HFWA call $\text{=====} \rightarrow S_2$
6	calculate thermodynamic state at 2s: $H_{t2}, S_{t2} = S_2$ vib froz HS call $\text{=====} \rightarrow P_{t2, \text{calc}}$
7	check for convergence on P_{t2} and adjust value of W
8	repeat steps 4 – 7 until desired convergence tolerance is reached (yields the vibrationally frozen state1 properties)
9	calculate the vibrationally relaxed state 1 properties: H_{t1}, F, W, A Equil vib HFWA call $\text{=====} \rightarrow$ vib relaxed state 1 properties
10	calculate the vibrationally relaxed state 1s properties: H_{t1}, S_{1vr} Equil vib HS call $\text{=====} \rightarrow$ vib relaxed state 1 properties

Table 4. Methodology used to determine the thermodynamic state at the nozzle exit plane

Facility Nozzle	Flight Enthalpy	PT1 (psia)	HST (btu/lb _m)	$W_{\text{flow meter}}$ (lb _m /s)	$W_{\text{frozen analysis}}$ (lb _m /s)	W % Difference
Mach 6	Mach 7	410	1040	4.45	4.39	1.3
Mach 6	Mach 6	495	795	6.10	6.10	0.0
Mach 6	Mach 5	400	650	5.41	5.48	-1.3
Mach 4.7	Mach 5	212	573	11.16	11.11	0.4
Mach 4.7	Mach 5.5	180	690	8.72	8.69	0.3
Mach 4.7	Mach 5 (ΔP_{t1})	178	580	9.30	9.37	-0.8

Table 5. Integrated mass flow results from vibrationally frozen analysis of the experimental nozzle calibration data

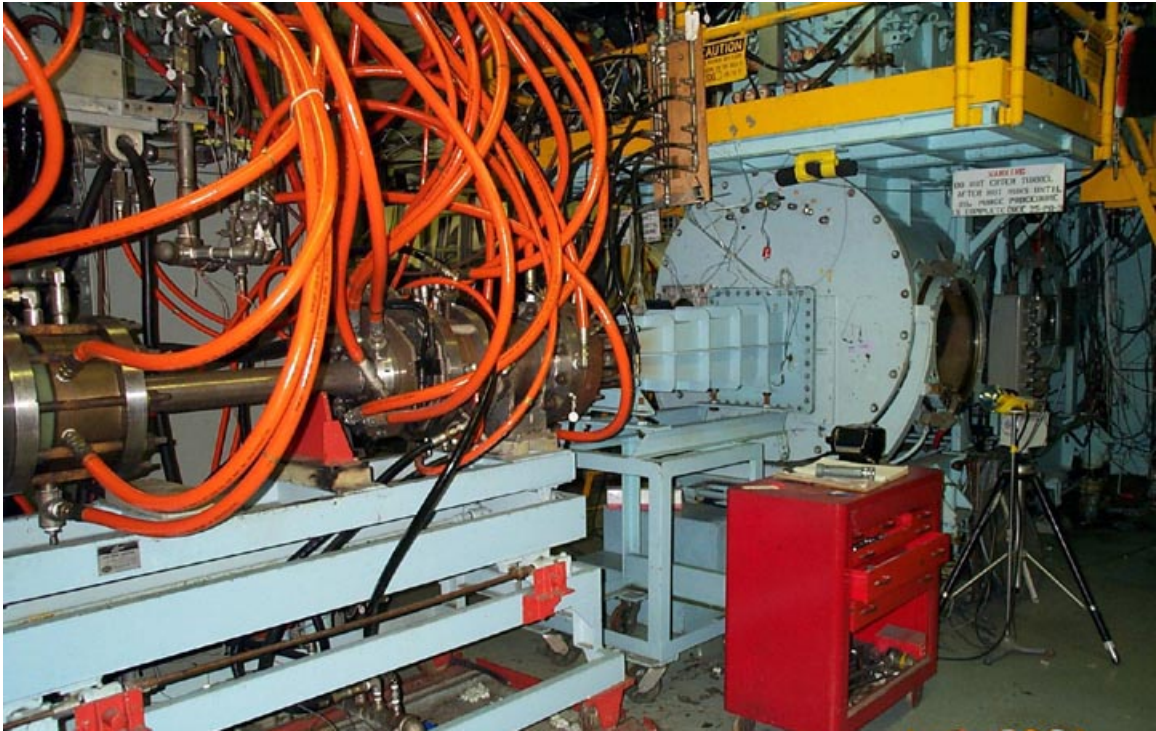


Figure 1. Photograph of the AHSTF (side view of facility nozzle and throat).

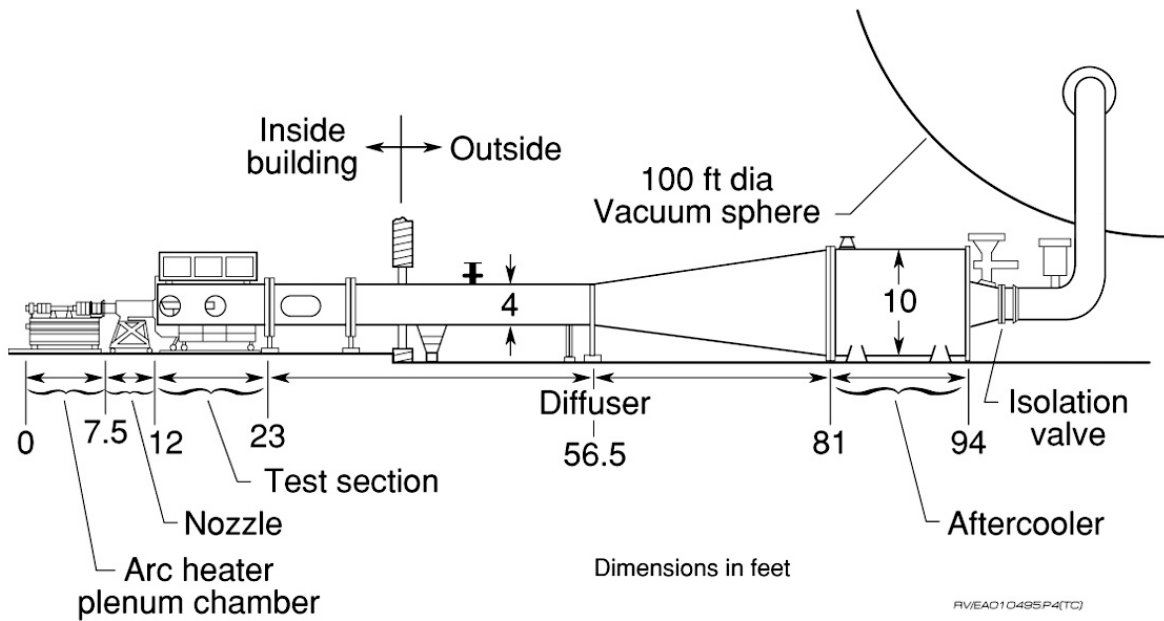


Figure 2. Arc-Heated Scramjet Test Facility.

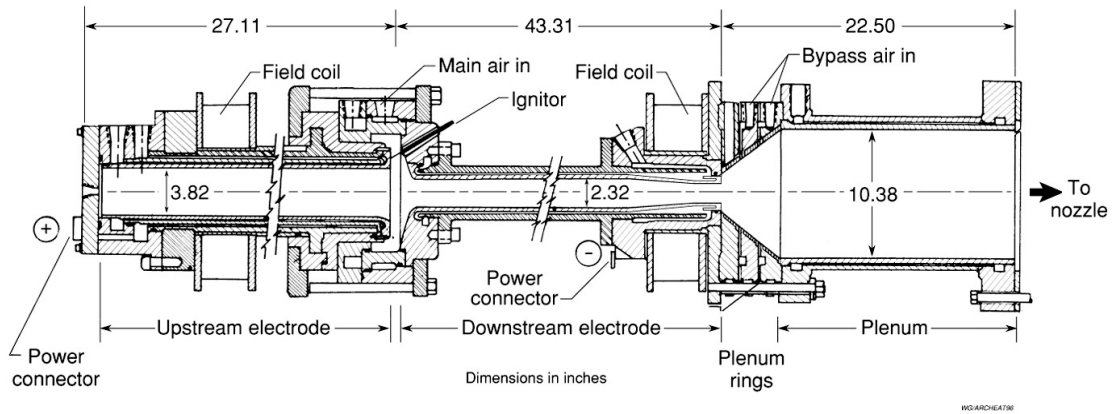


Figure 3. AHSTF heater and plenum chamber.

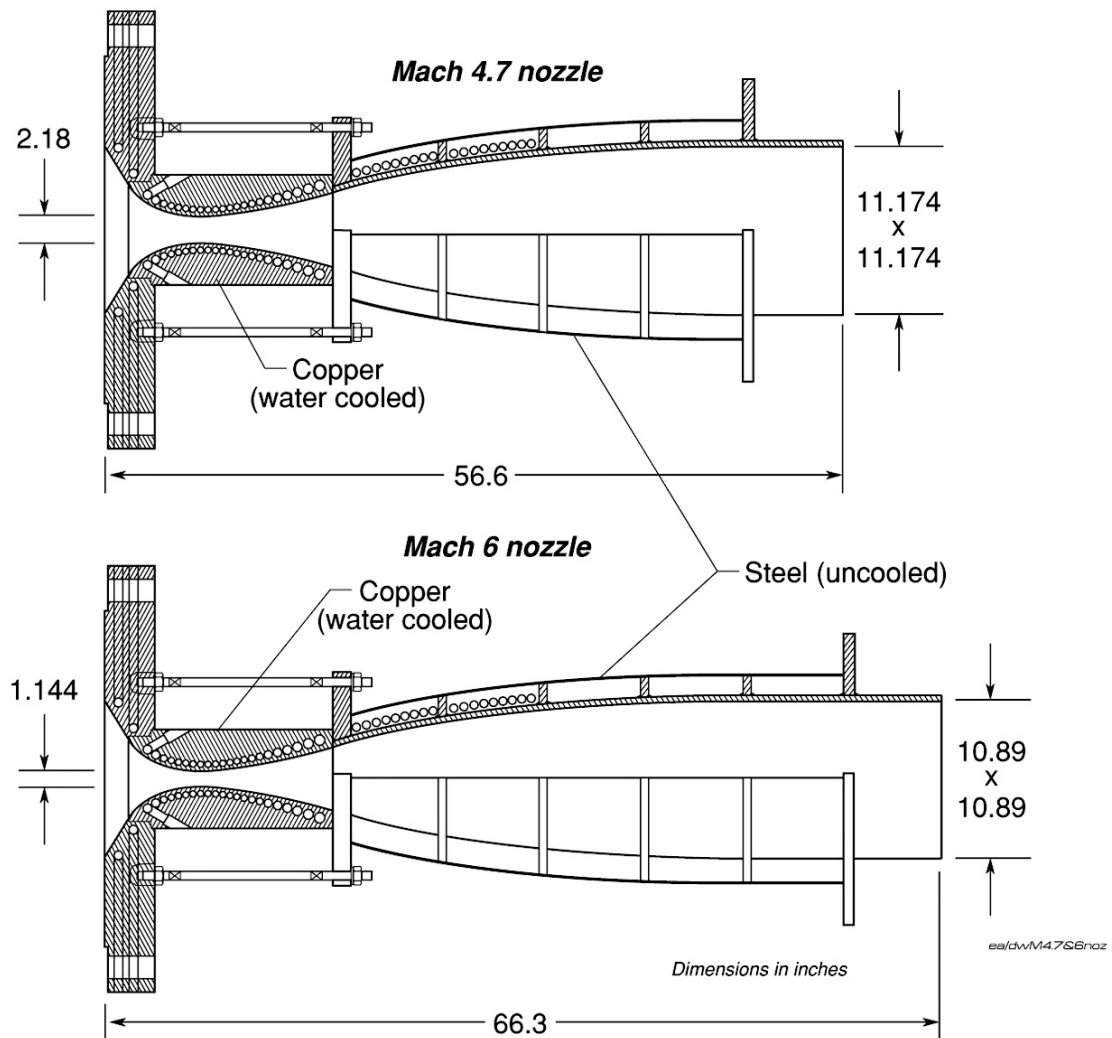


Figure 4. Schematics of the Mach 4.7 and Mach 6 square cross section AHSTF nozzles.

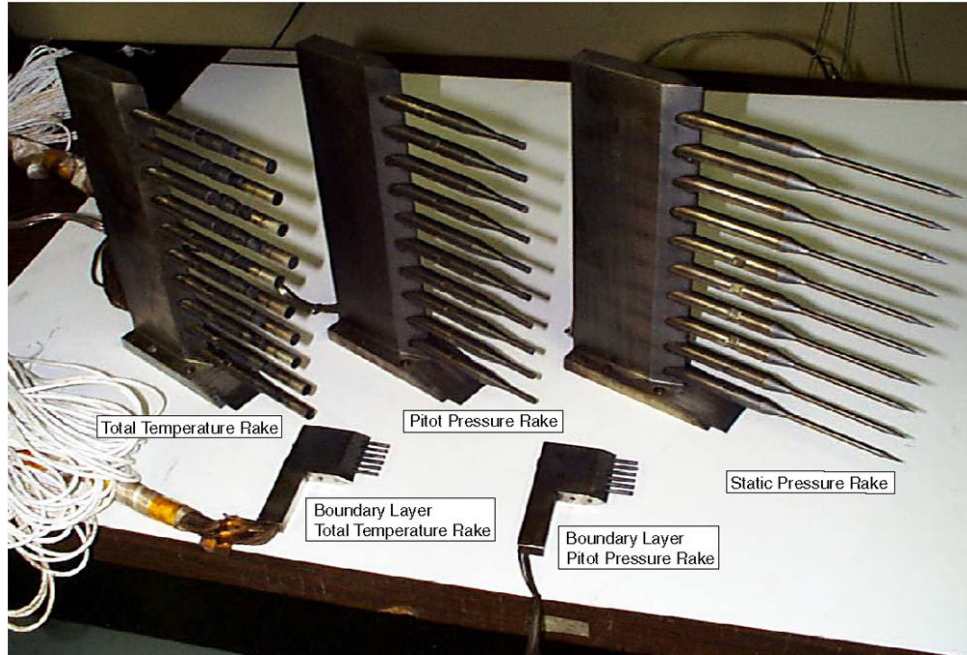
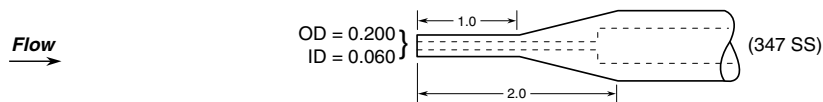


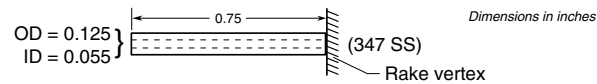
Figure 5. Photograph of the AHSTF nozzle calibration instrumentation.

AHSTF CALIBRATION INSTRUMENTATION

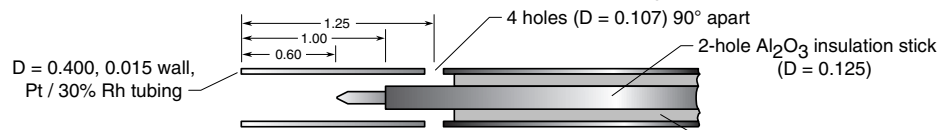
Pitot probe (Core flow): 10 mounted in rake at 1 inch spacing



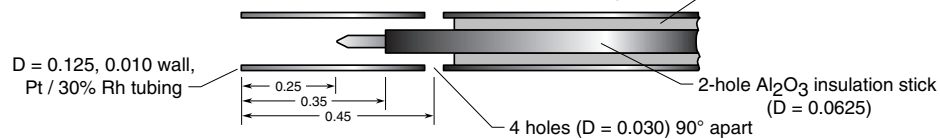
Pitot probe (BL): 6 mounted in rake at 0.25 inch spacing



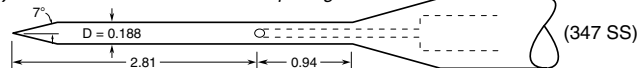
Total temperature probe (Core flow): 10 mounted in rake at 1 inch spacing



Total temperature probe (BL): 6 mounted in rake at 0.25 inch spacing



Static pressure probe (Core flow): 10 mounted in rake at 1 inch spacing



Sidewall static pressures: 10 on each of the 4 walls at 1 inch spacing

DW05142001.eps

Figure 6. Instrumentation schematics detailing the geometry and material design for each measurement probe.

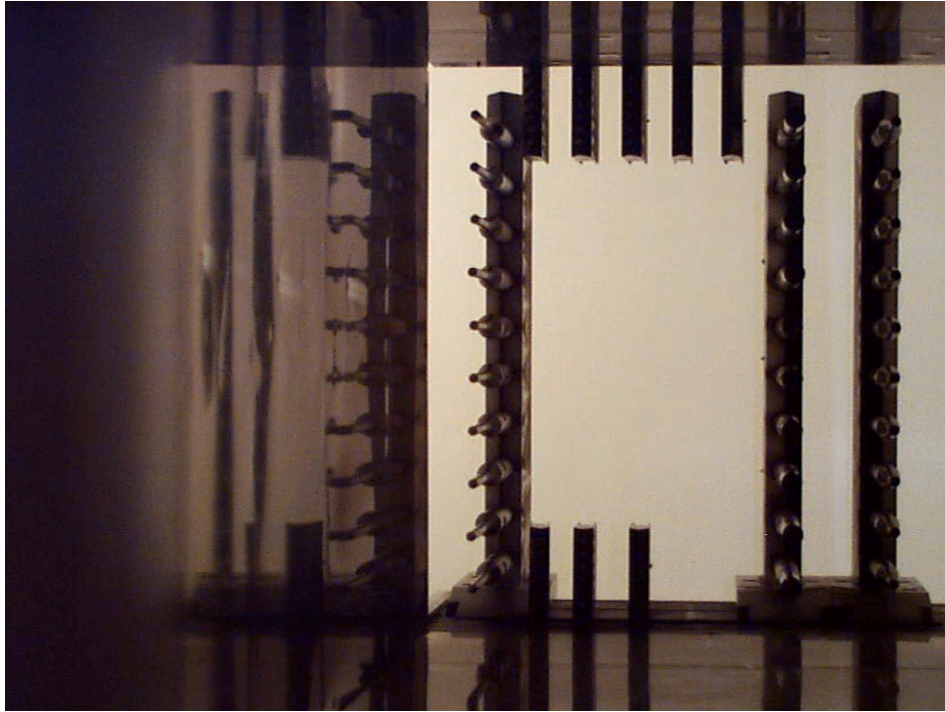


Figure 7. View from the nozzle throat of the calibration probes installed at the nozzle exit.

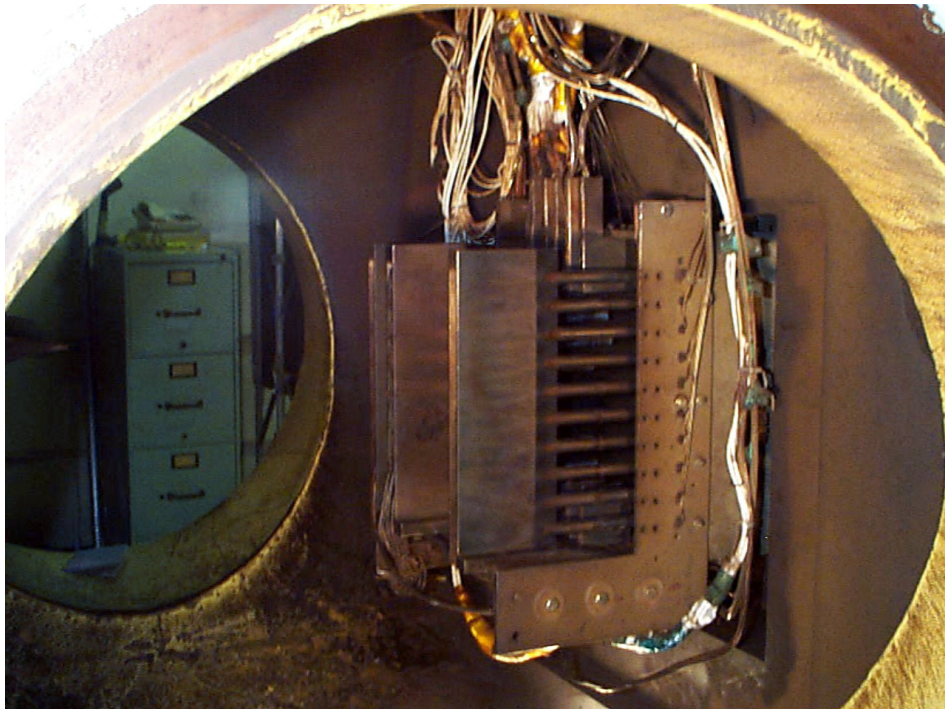


Figure 8. View from the test section door of the calibration probes installed at the nozzle exit.

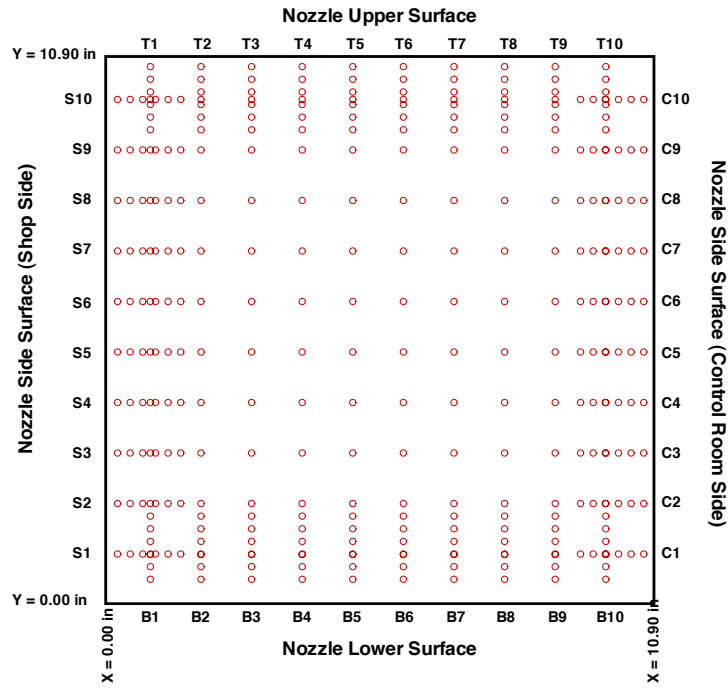


Figure 9. Probe survey locations at the facility nozzle exit plane.

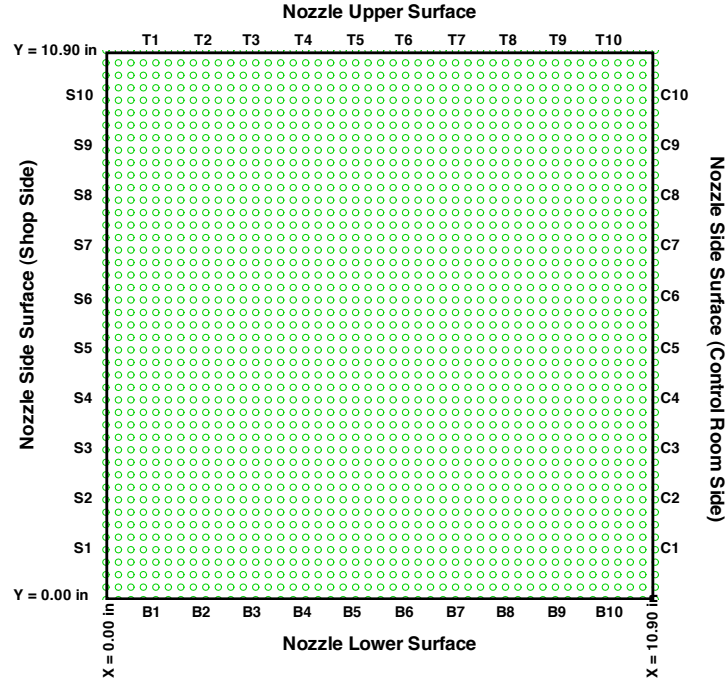


Figure 10. Plot of interpolated data locations.

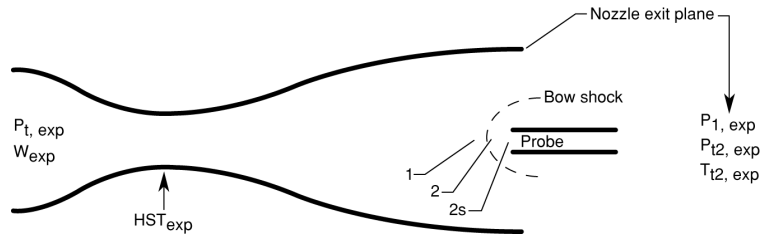


Figure 11. Location of nozzle exit parameters

RESULTS:

Mach 4.7 Nozzle, Mach 5 H_t Test Condition

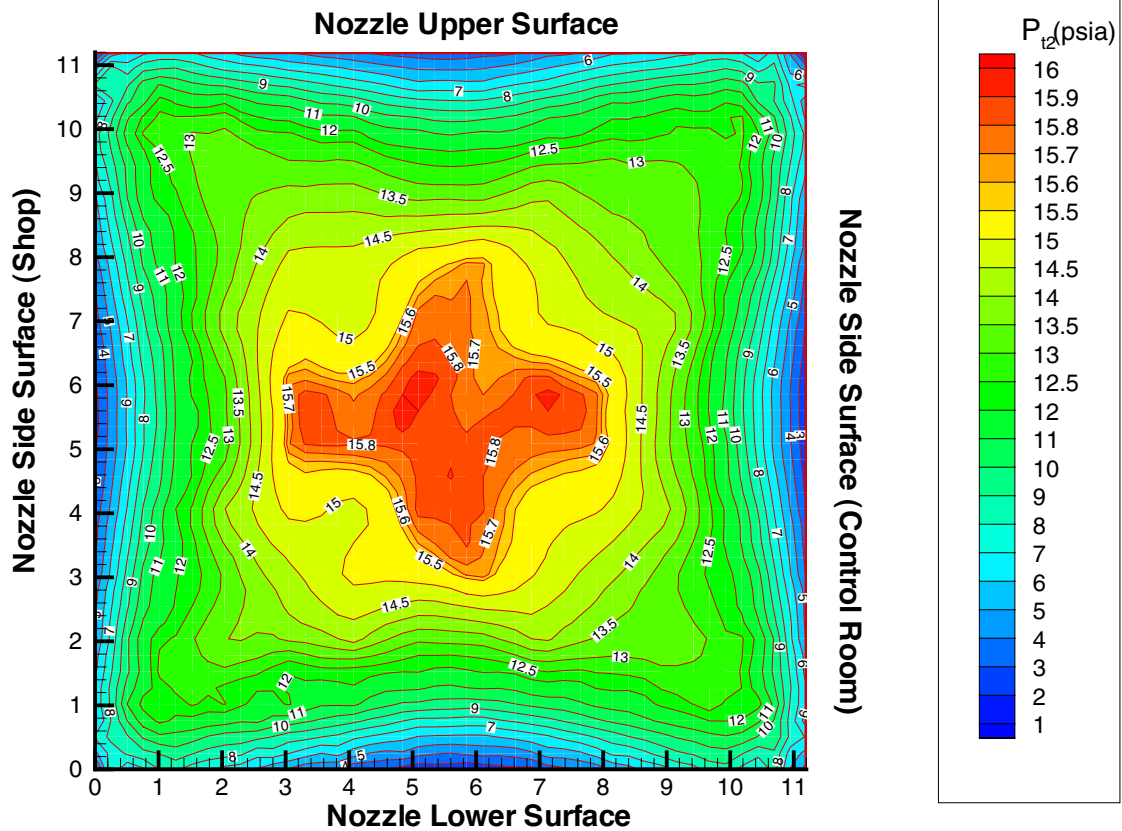


Figure 12a. Pitot pressure contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point ($PT1 = 212$ psia, $HST = 573$ btu/lbm). All dimensions are in inches.

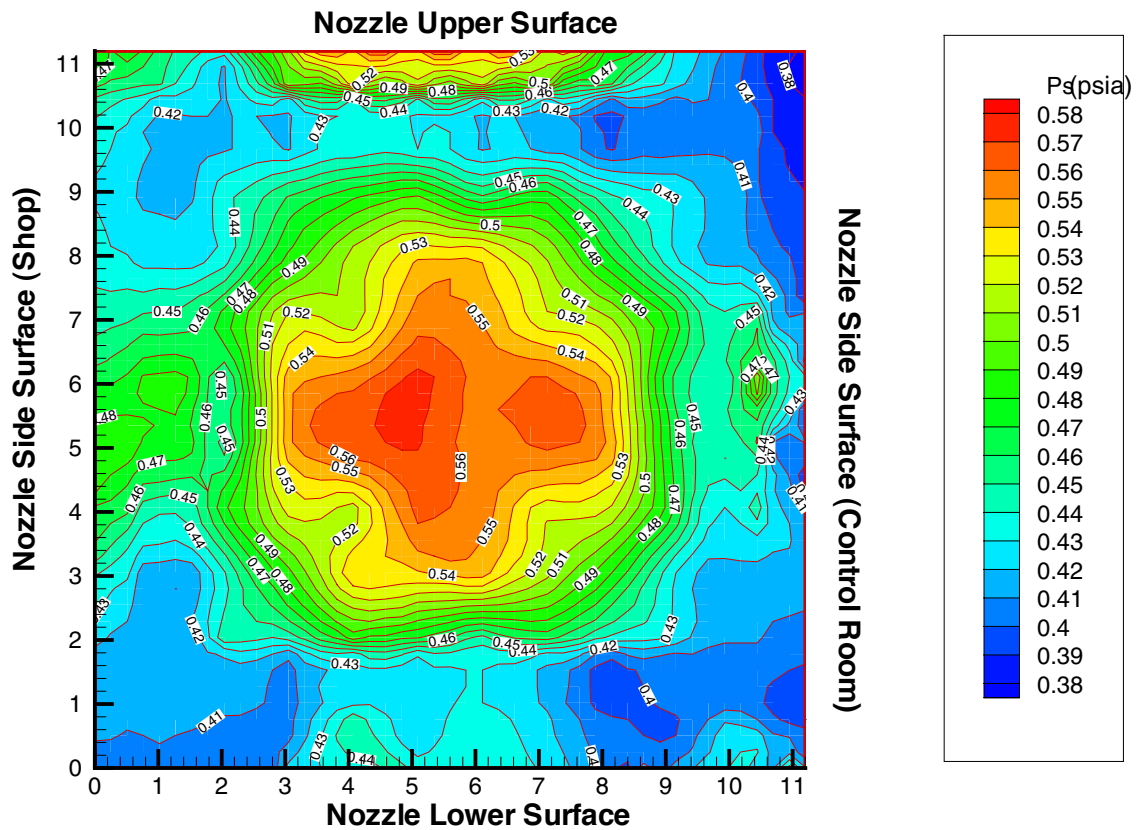


Figure 12b. Static pressure contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point ($PT1 = 212$ psia, $HST = 573$ btu/lbm). All dimensions are in inches.

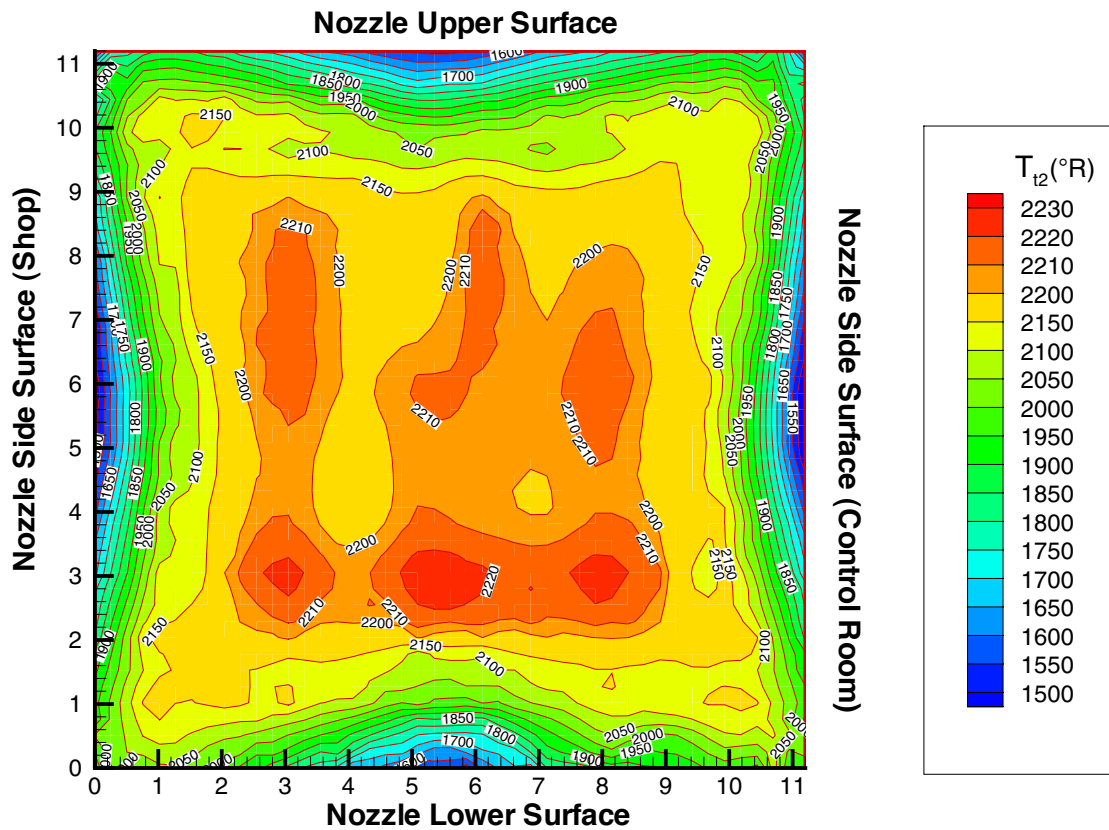


Figure 12c. Total temperature contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

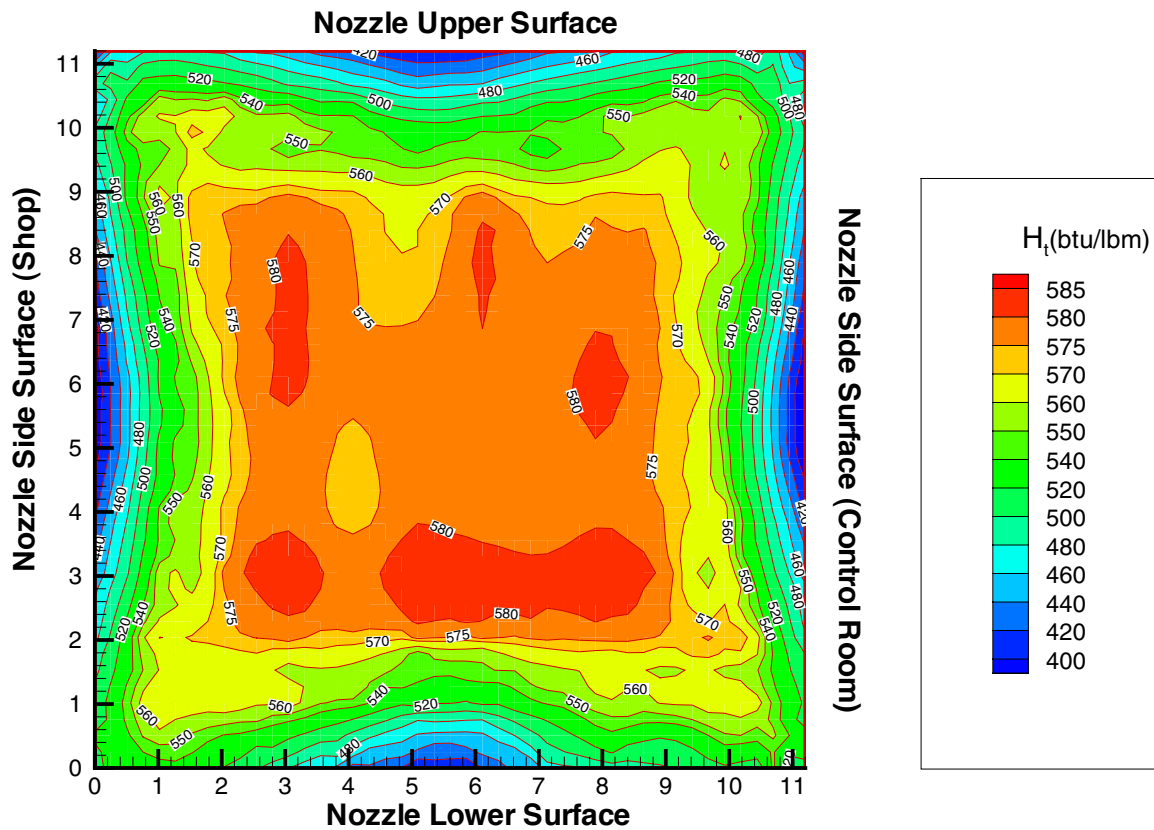


Figure 12d. Total enthalpy contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

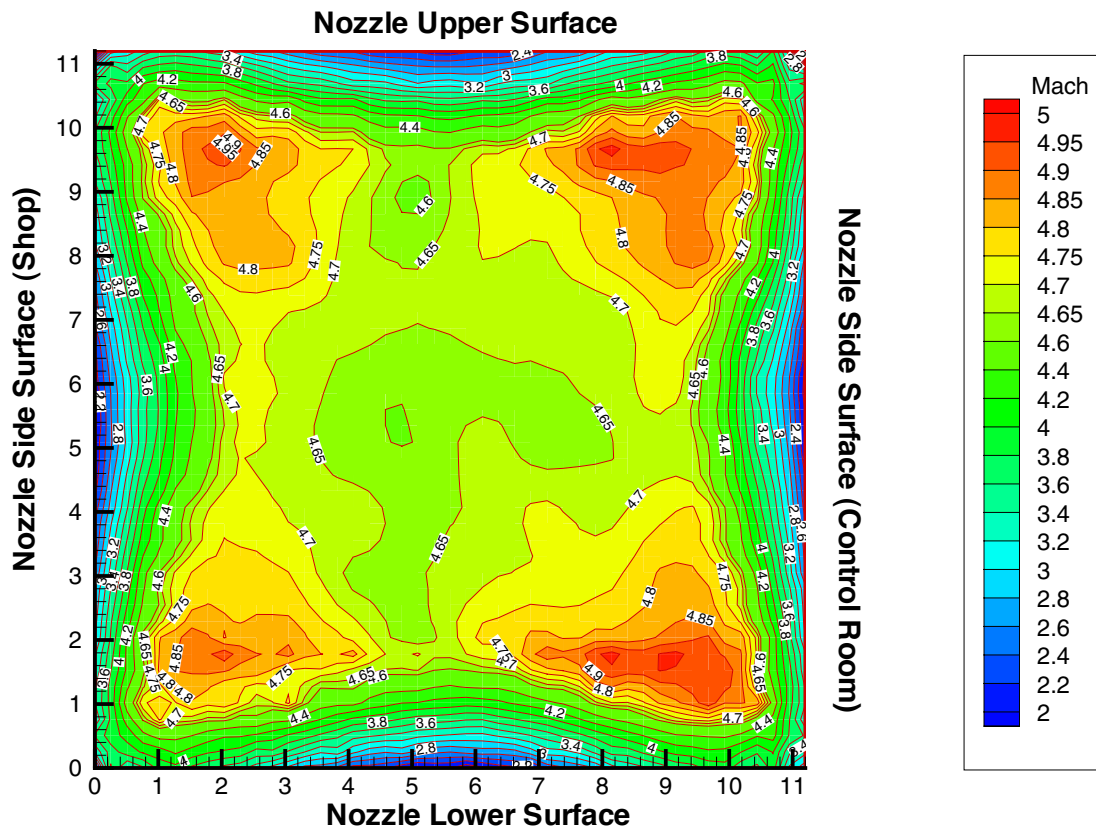


Figure 12e. Mach contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

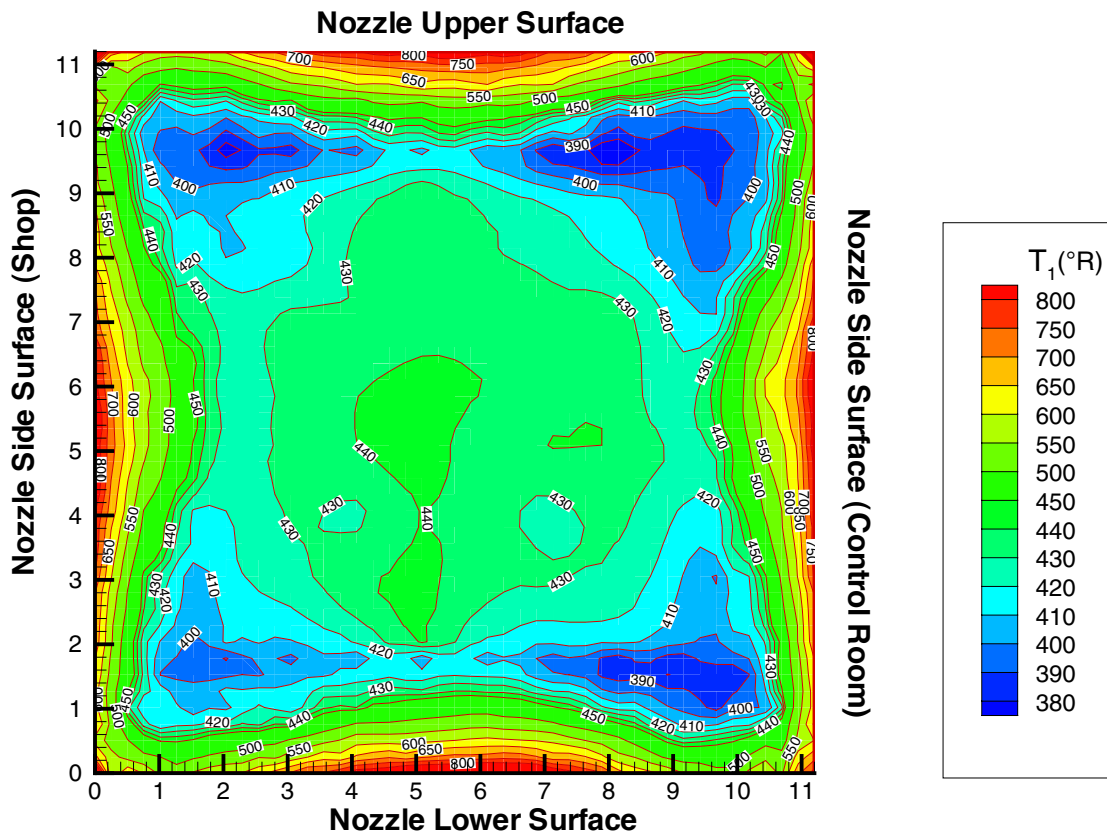


Figure 12f. Static temperature contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

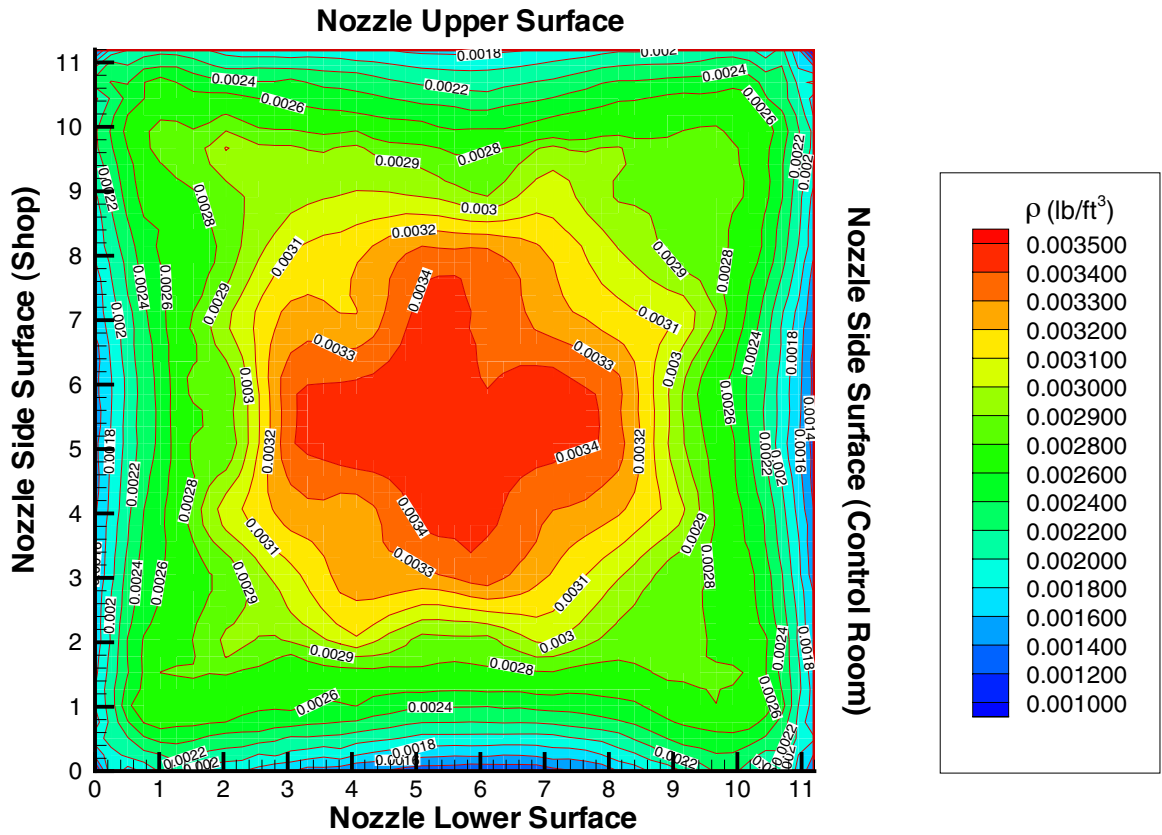


Figure 12g. Static density contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

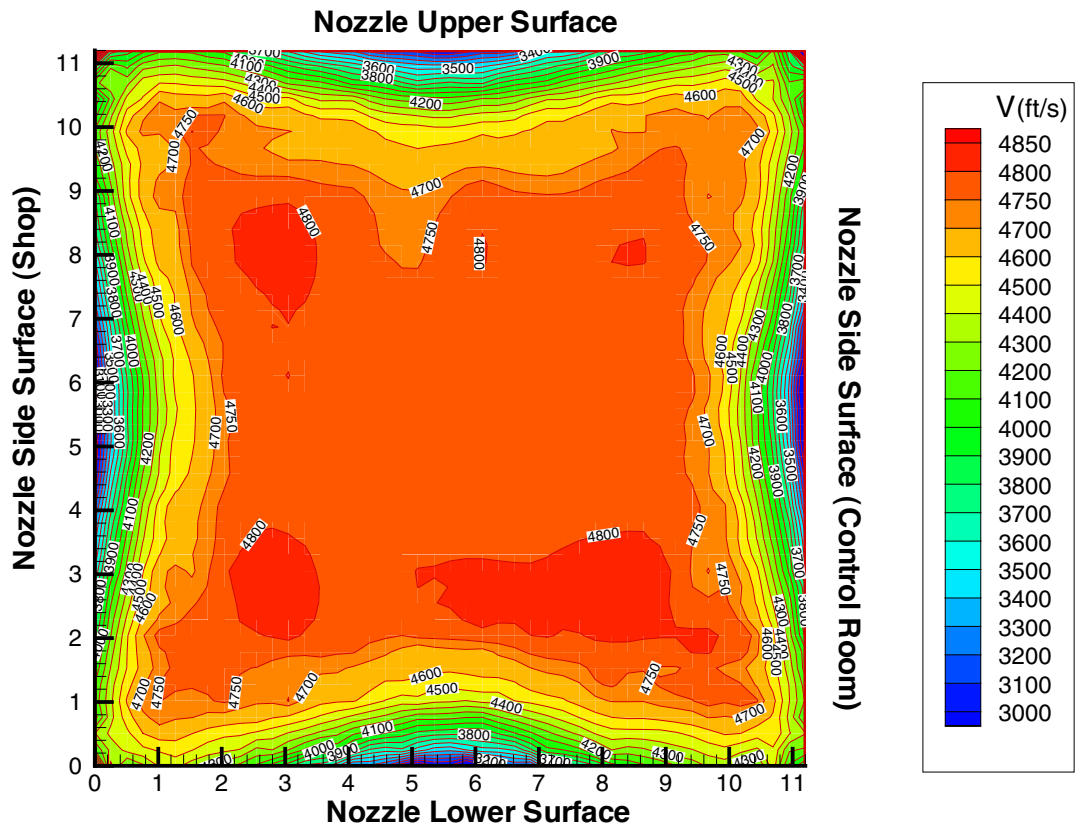


Figure 12h. Velocity contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

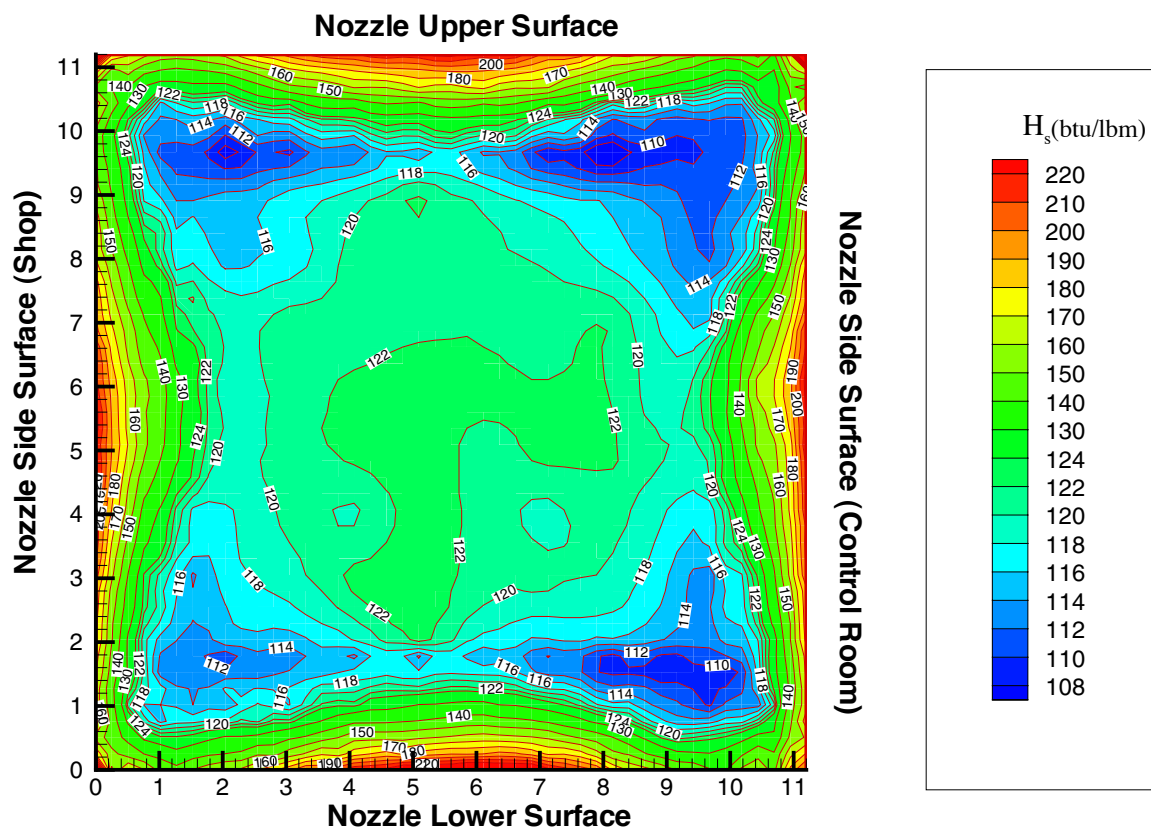


Figure 12i. Static enthalpy contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

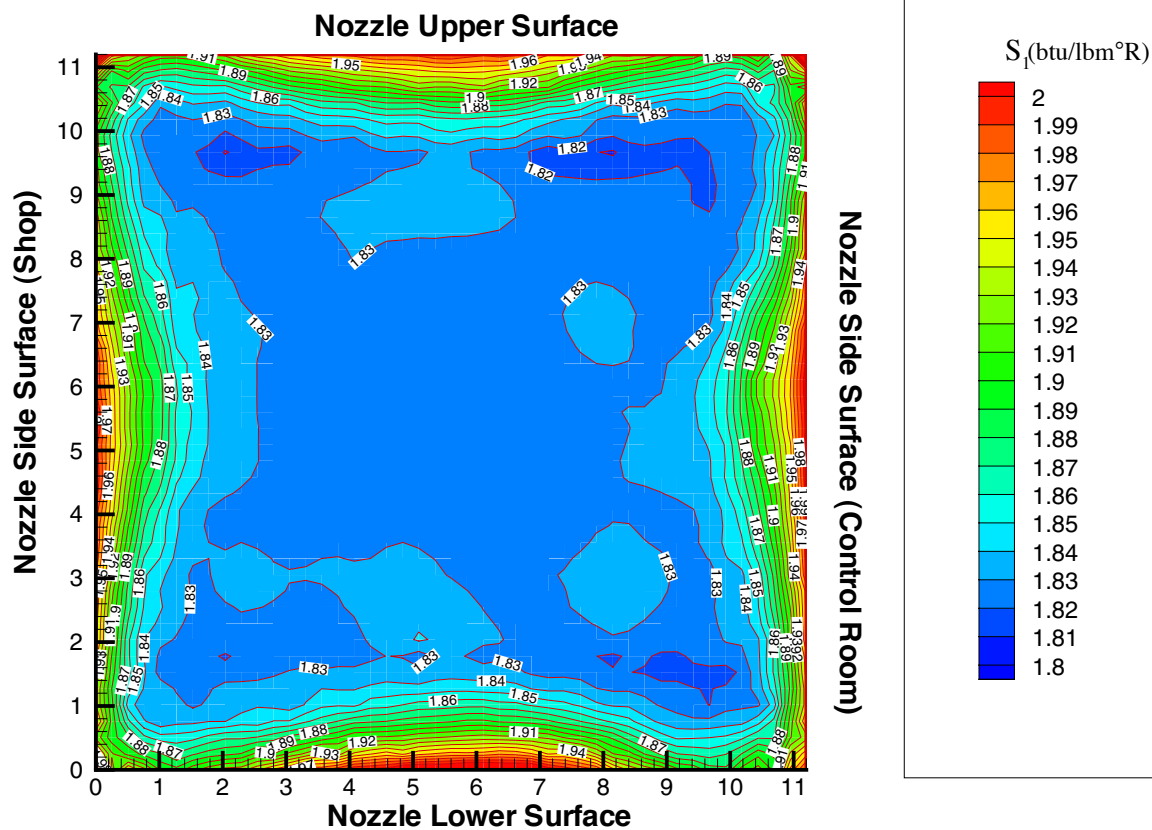


Figure 12j. Entropy contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point ($PT_1 = 212$ psia, $HST = 573$ btu/lbm). All dimensions are in inches.

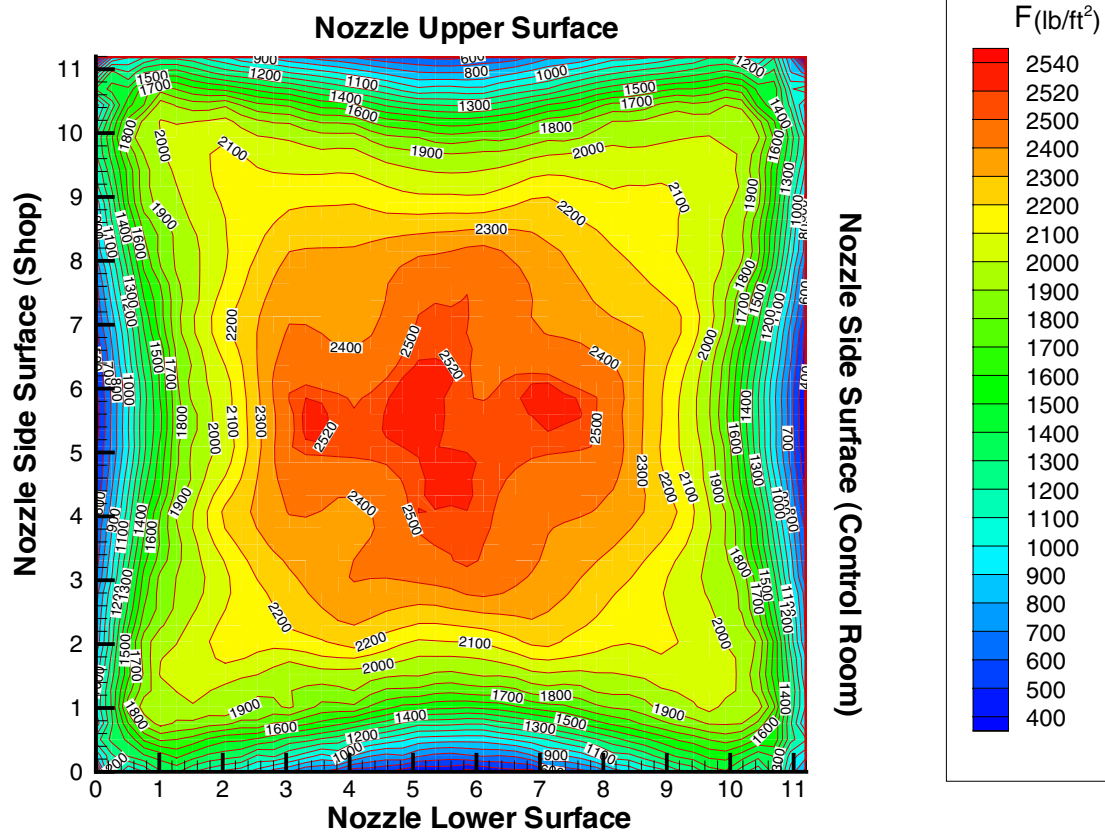


Figure 12k. Stream thrust contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

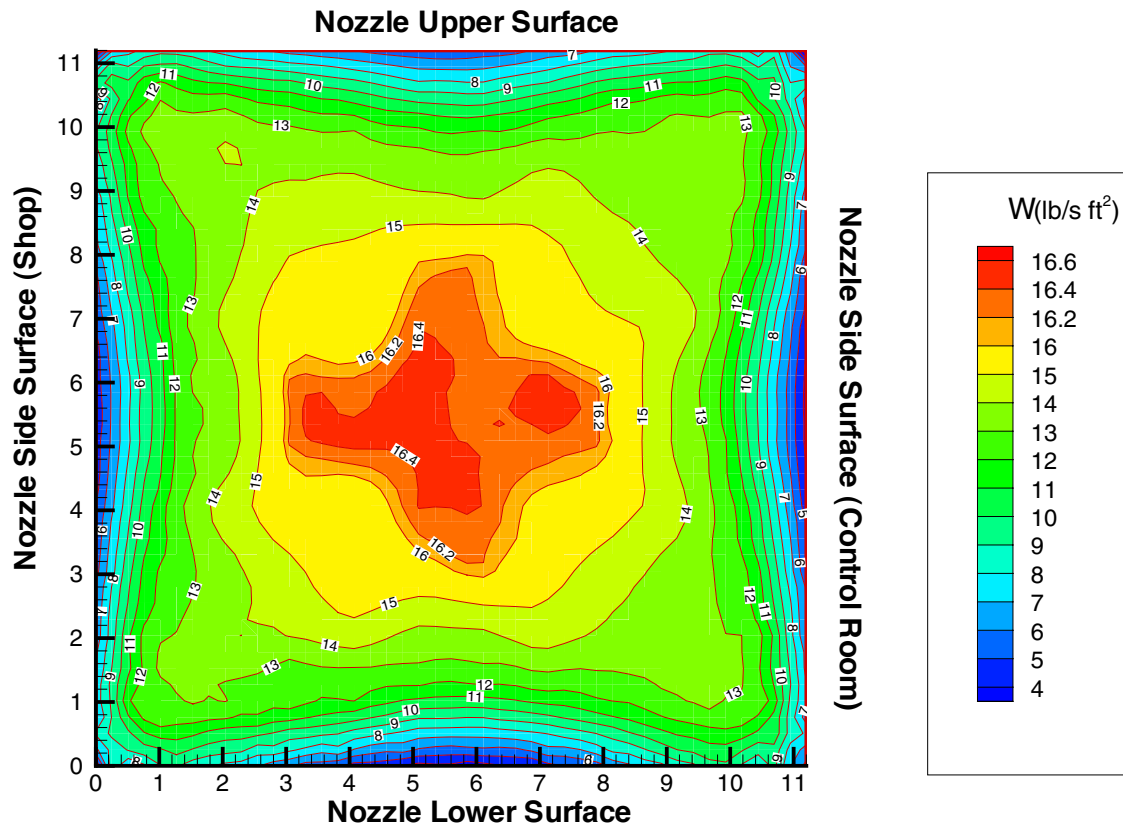


Figure 12l. Mass flux contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

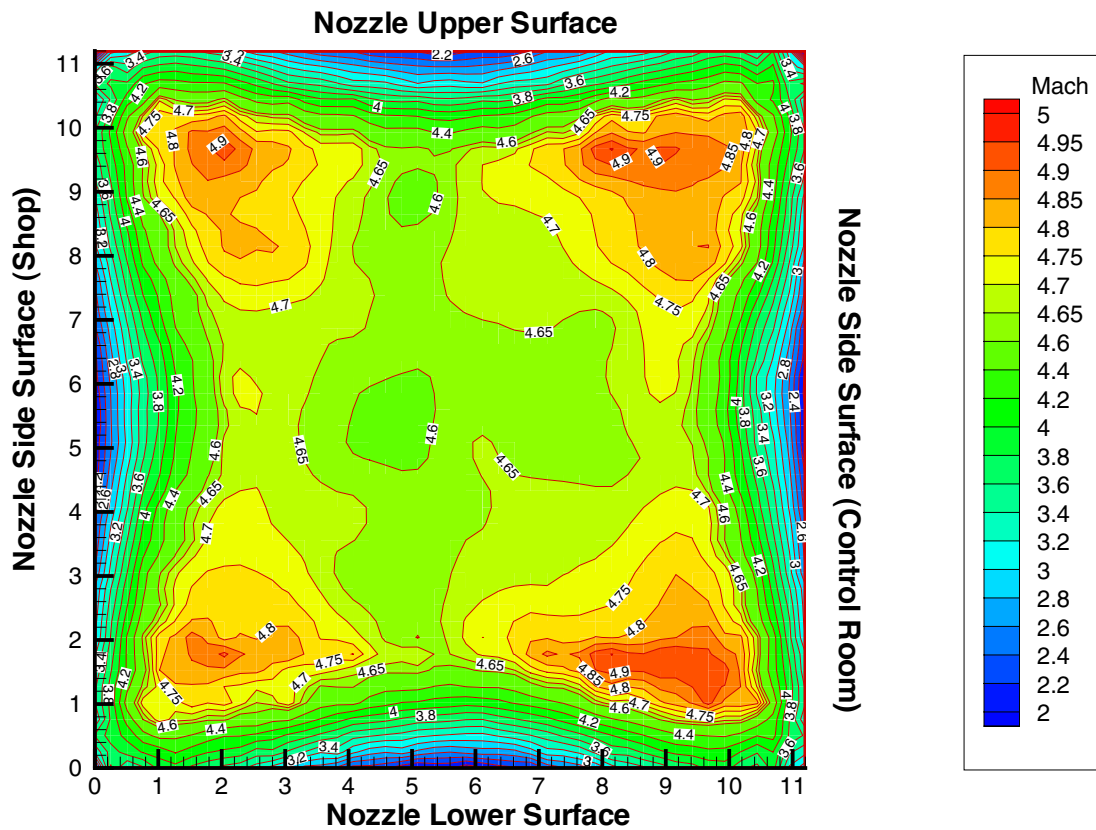


Figure 12m. Mach contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

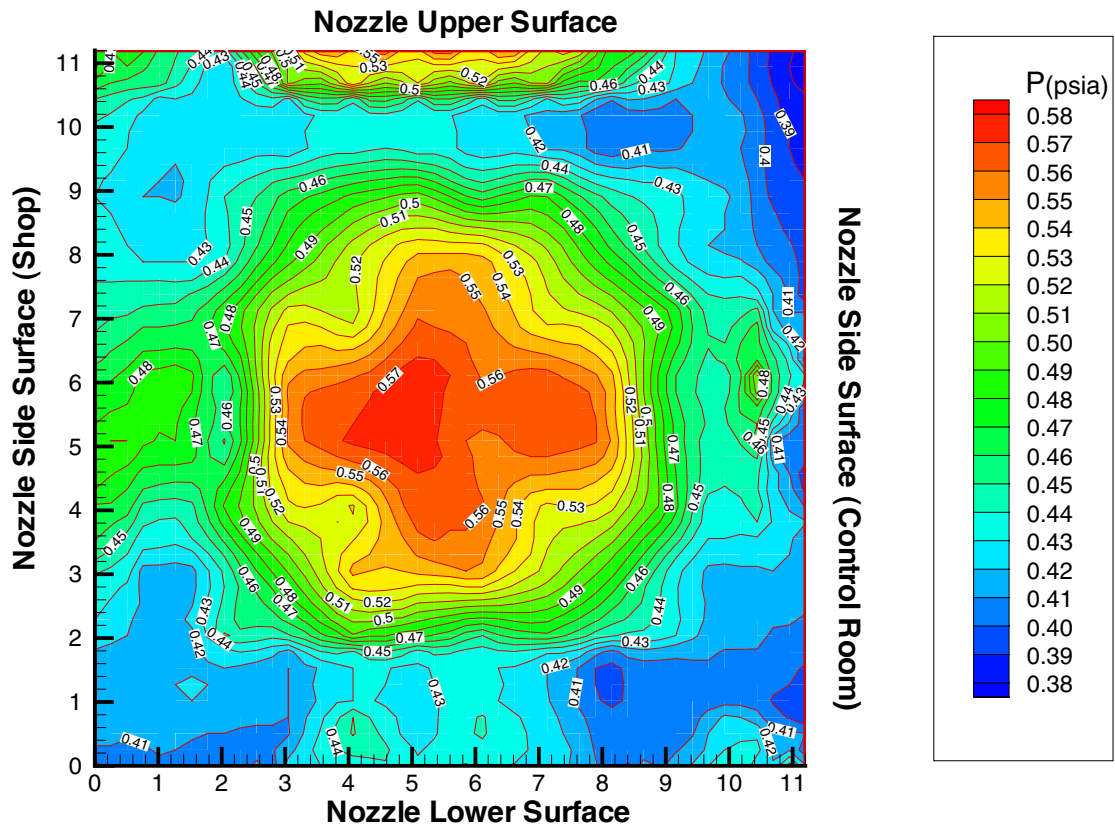


Figure 12n. Static pressure contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

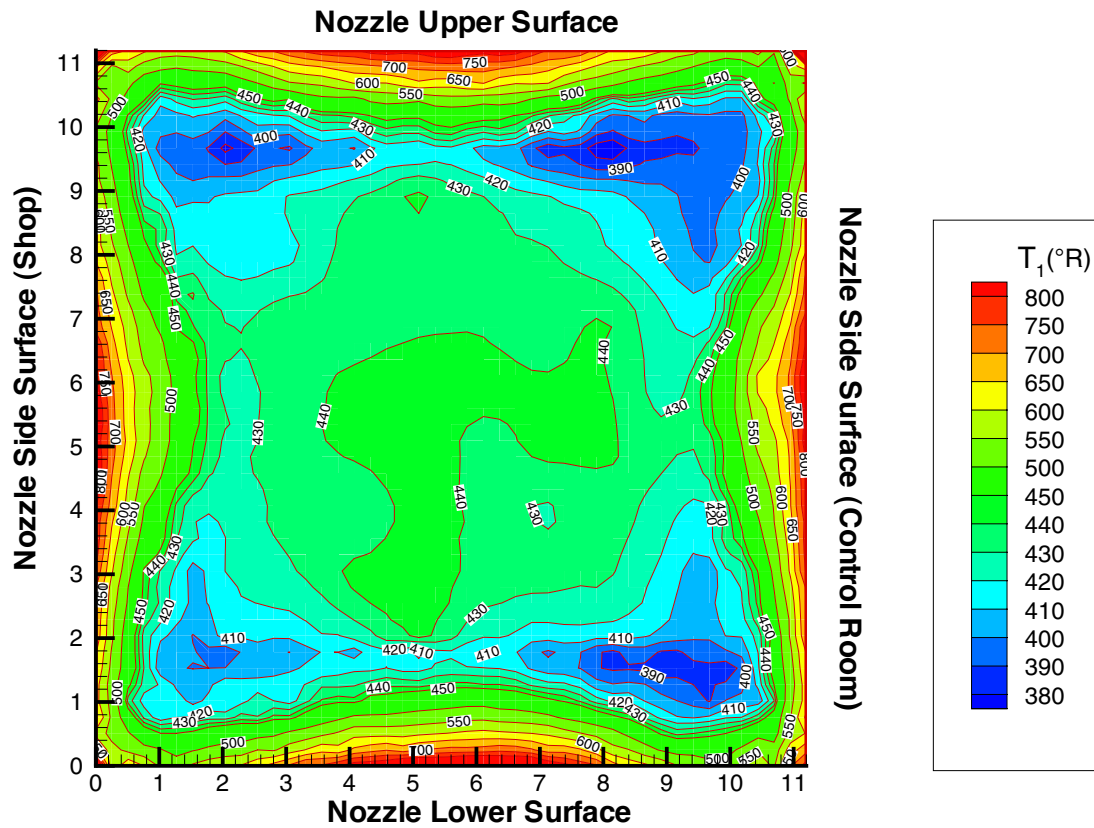


Figure 12o. Static temperature contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

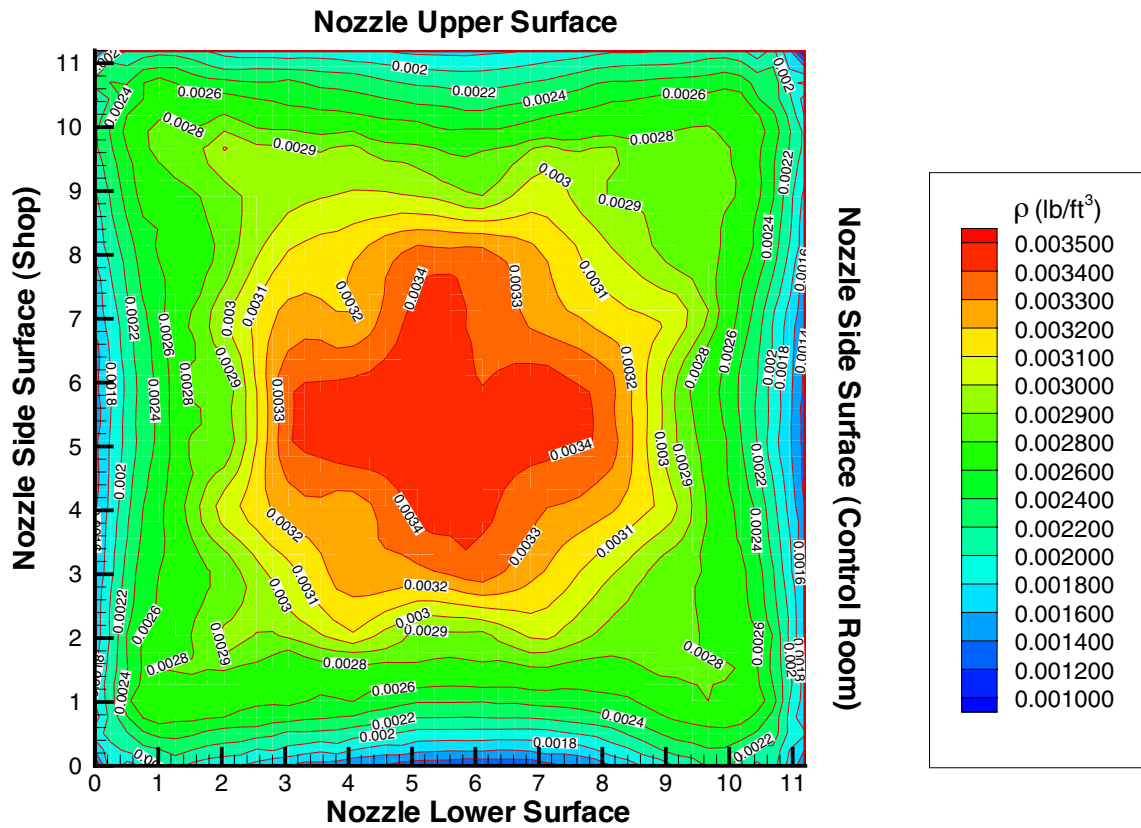


Figure 12p. Static density contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

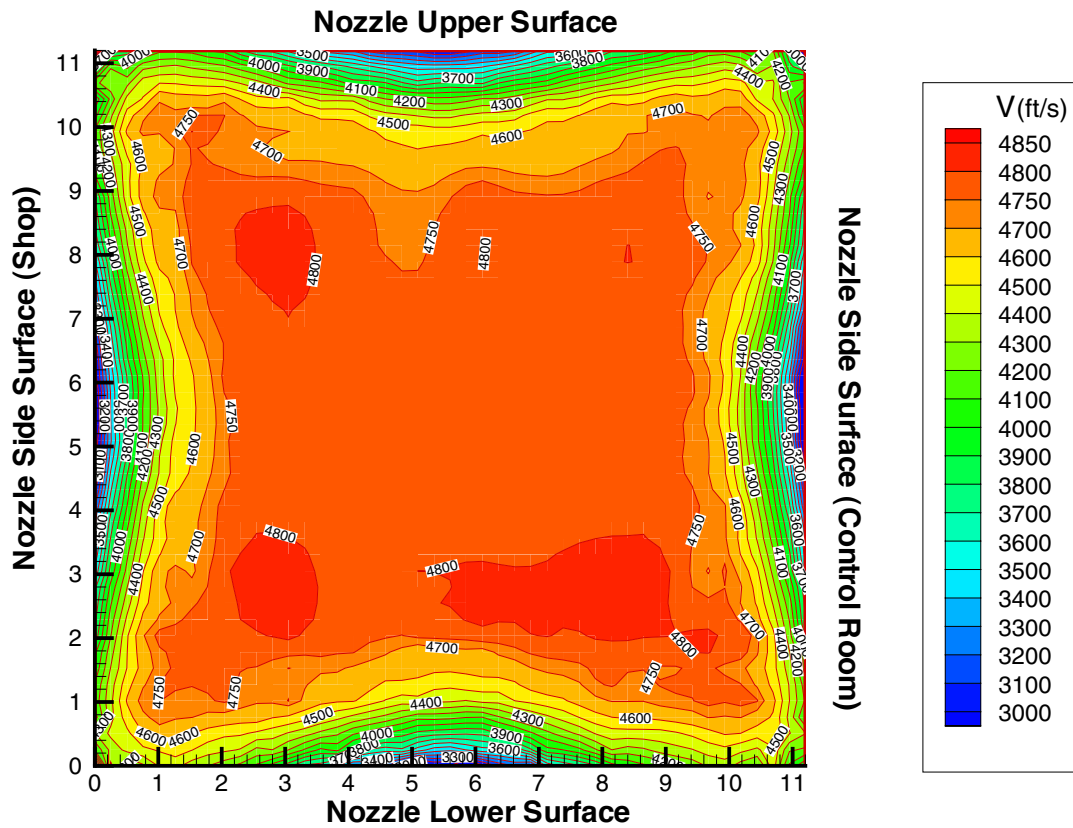


Figure 12q. Velocity contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

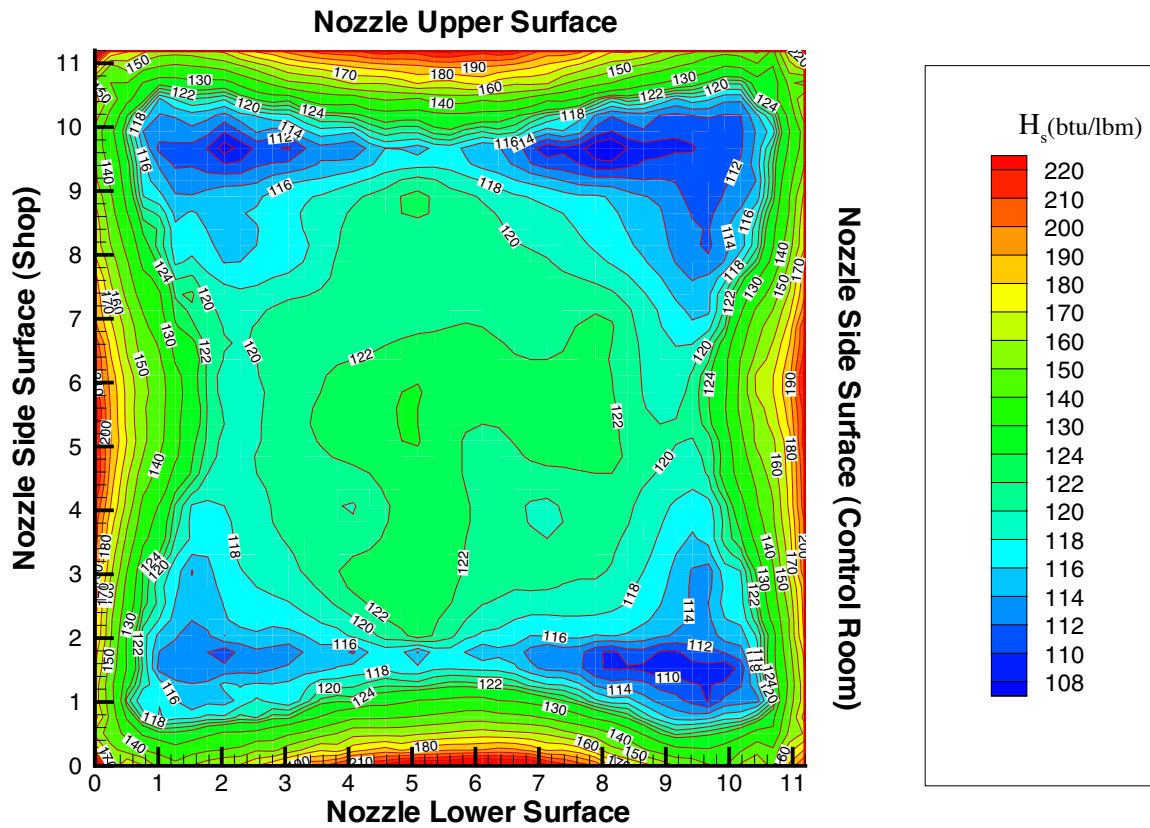


Figure 12r. Static enthalpy contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

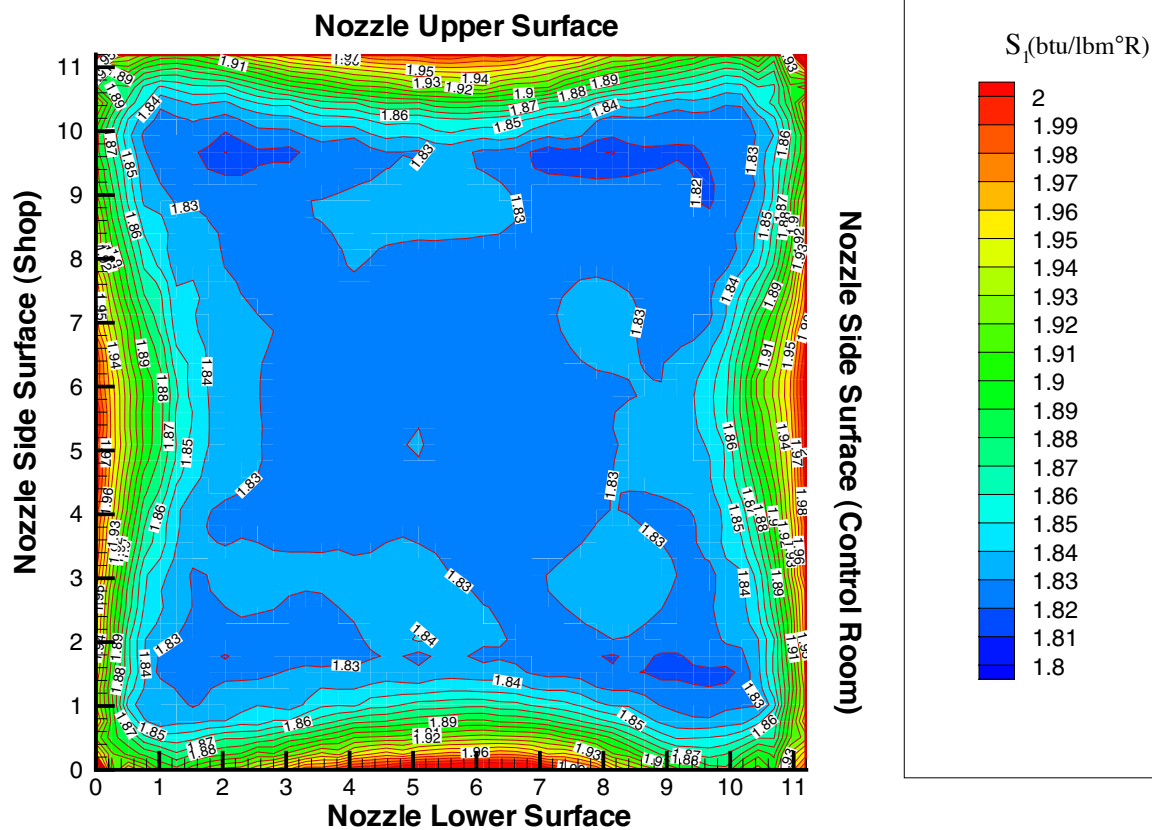


Figure 12s. Entropy contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

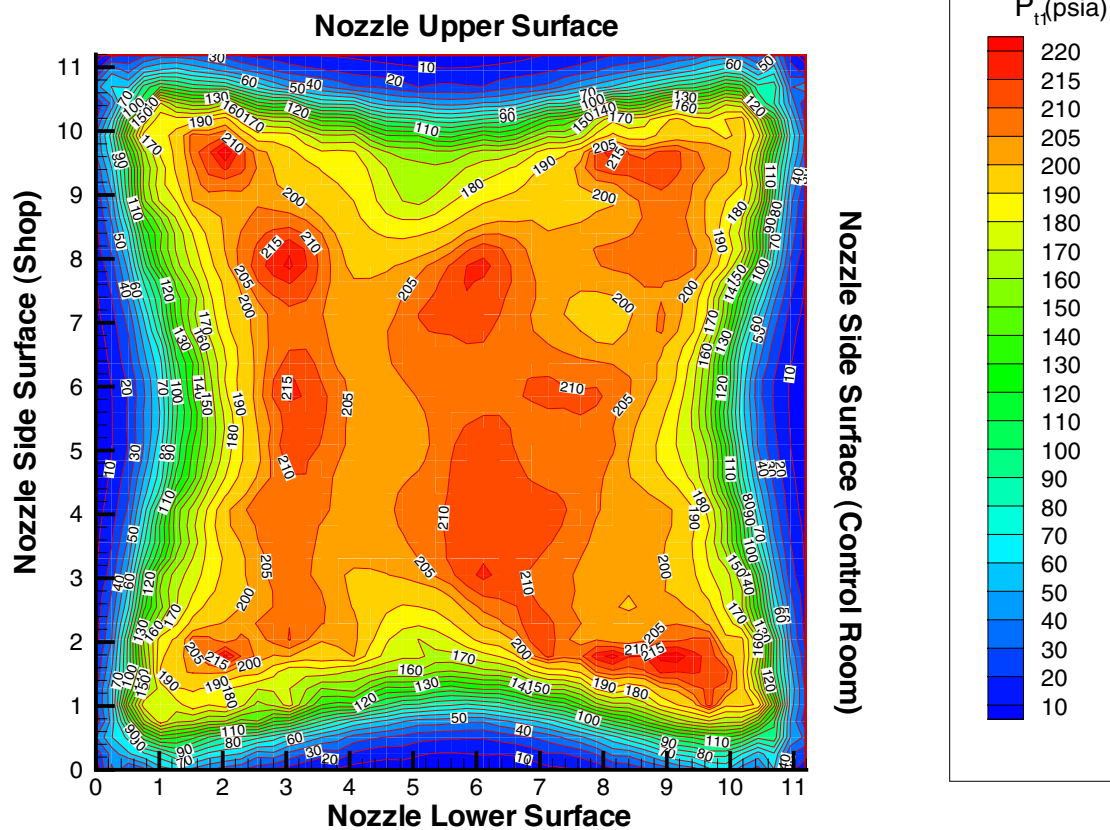


Figure 12t. Freestream total pressure contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

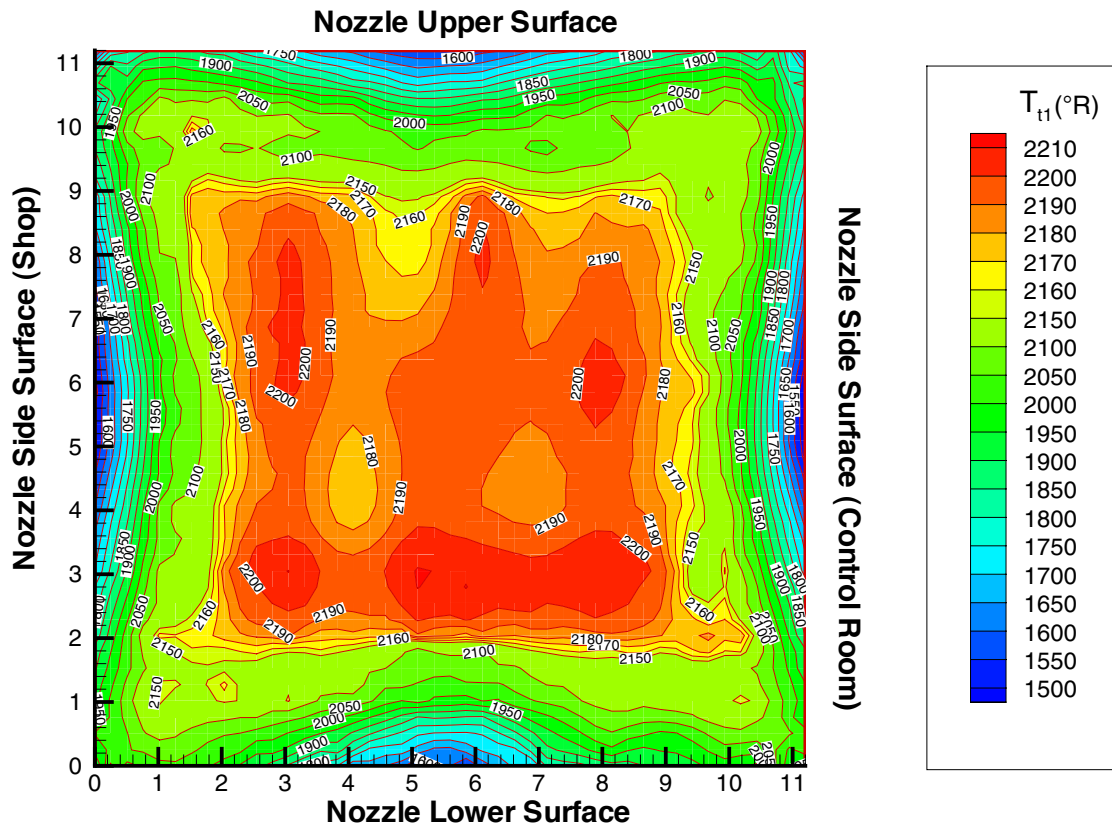


Figure 12u. Freestream total temperature contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

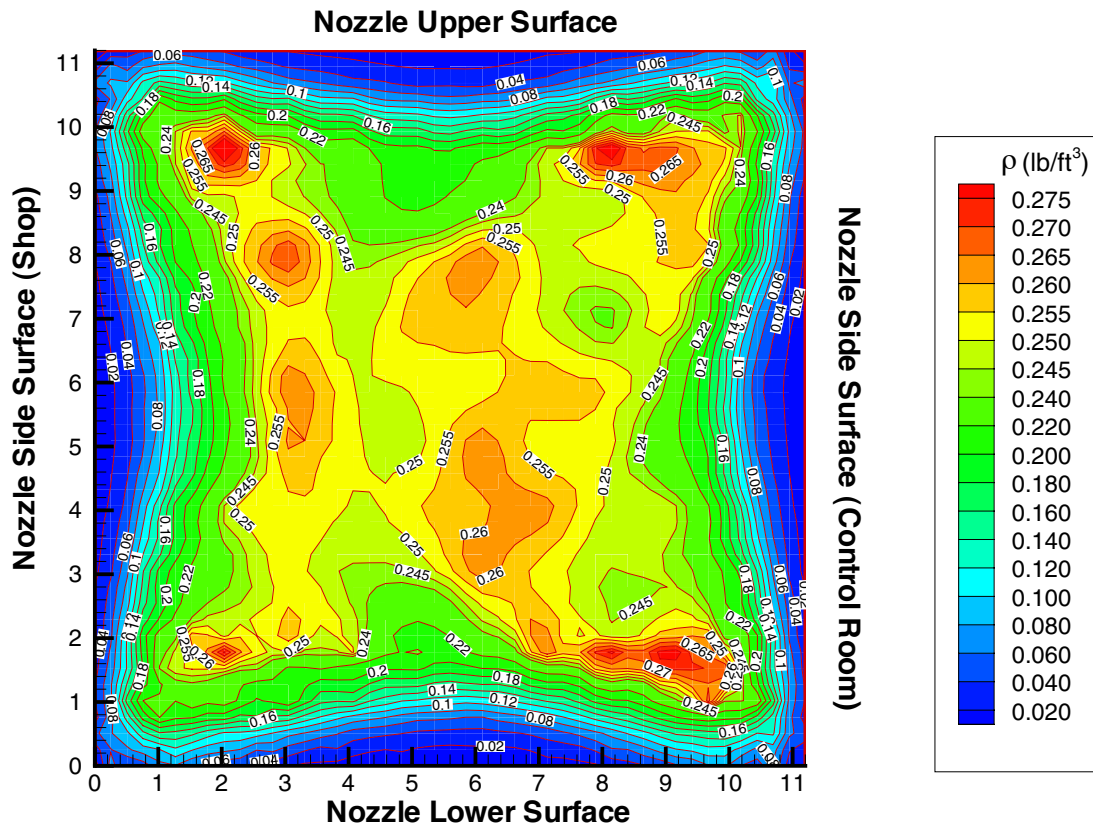


Figure 12v. Freestream total density contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 212 psia, HST = 573 btu/lbm). All dimensions are in inches.

Mach 4.7 Nozzle, Mach 5.5 H_t Test Condition

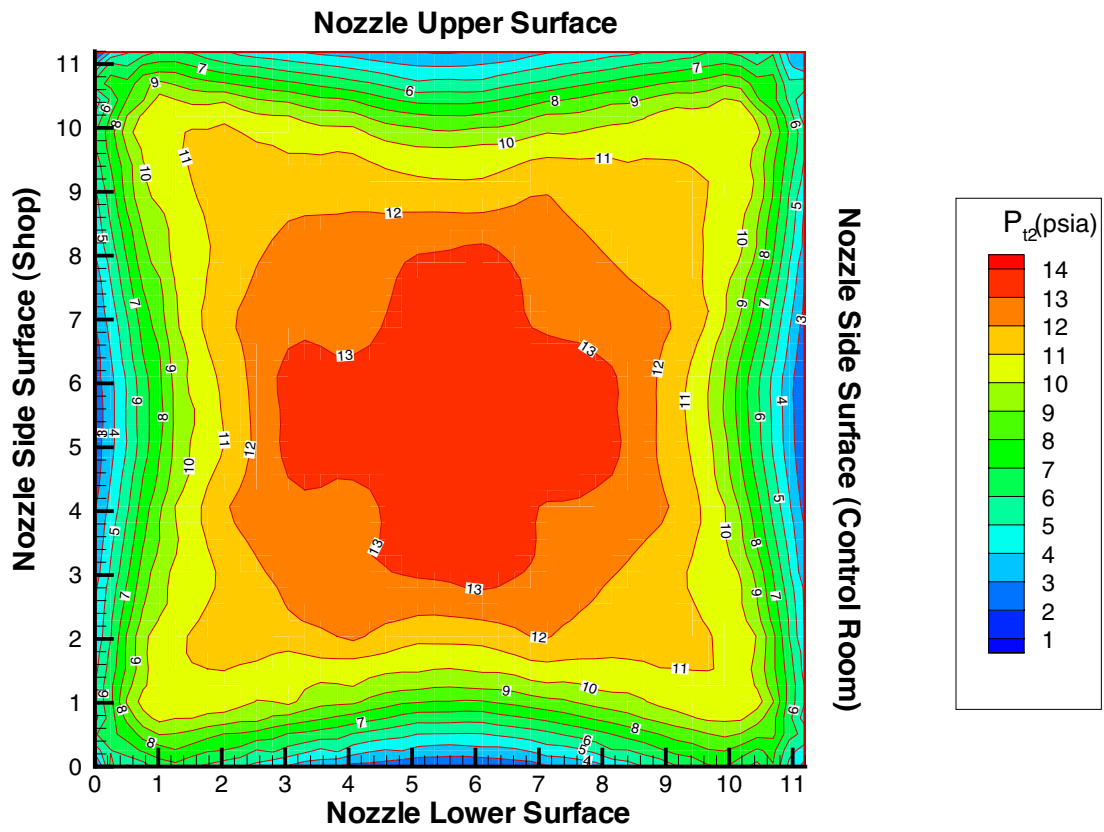


Figure 13a. Pitot pressure contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point ($PT1 = 180$ psia, $HST = 690$ btu/lbm). All dimensions are in inches.

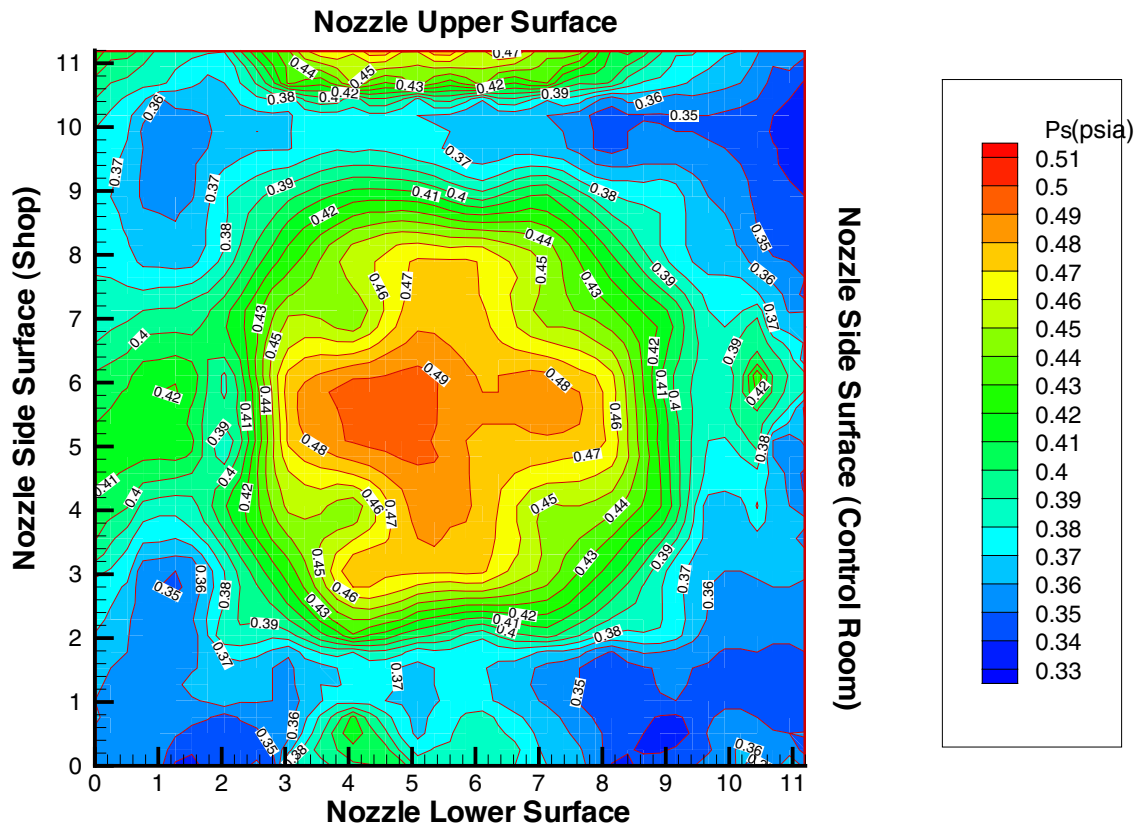


Figure 13b. Static pressure contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

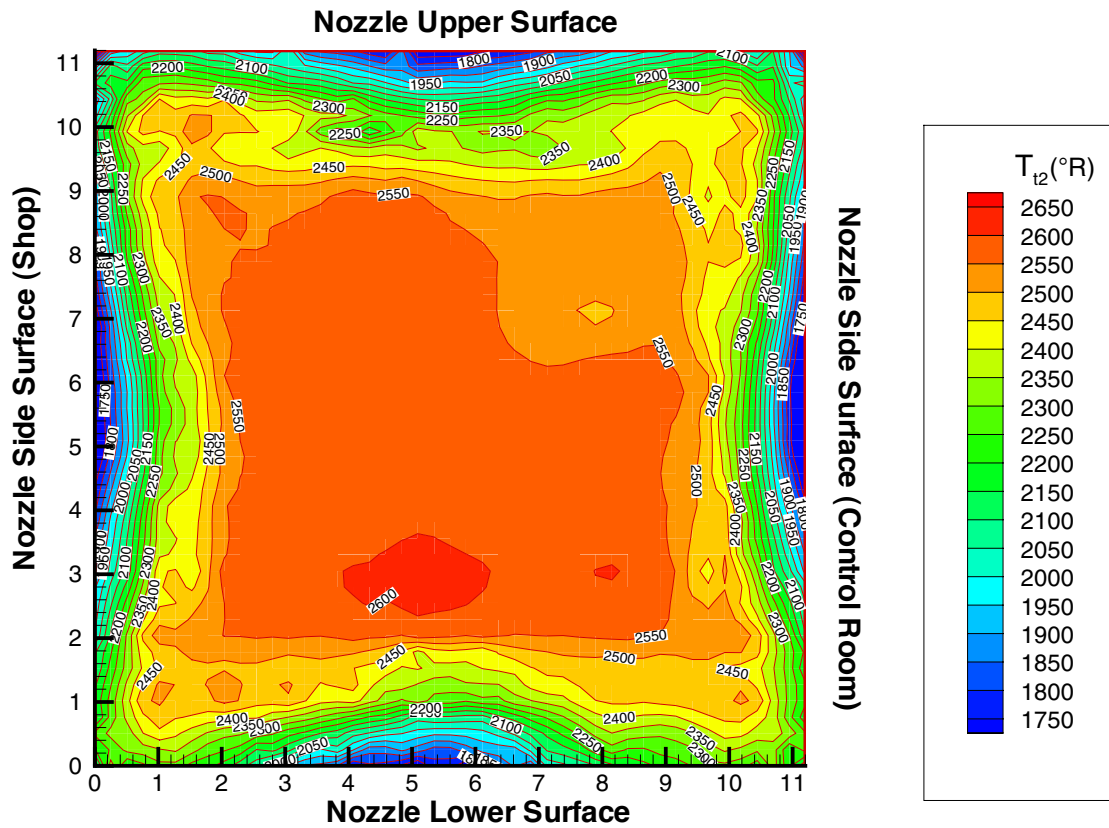


Figure 13c. Total temperature contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

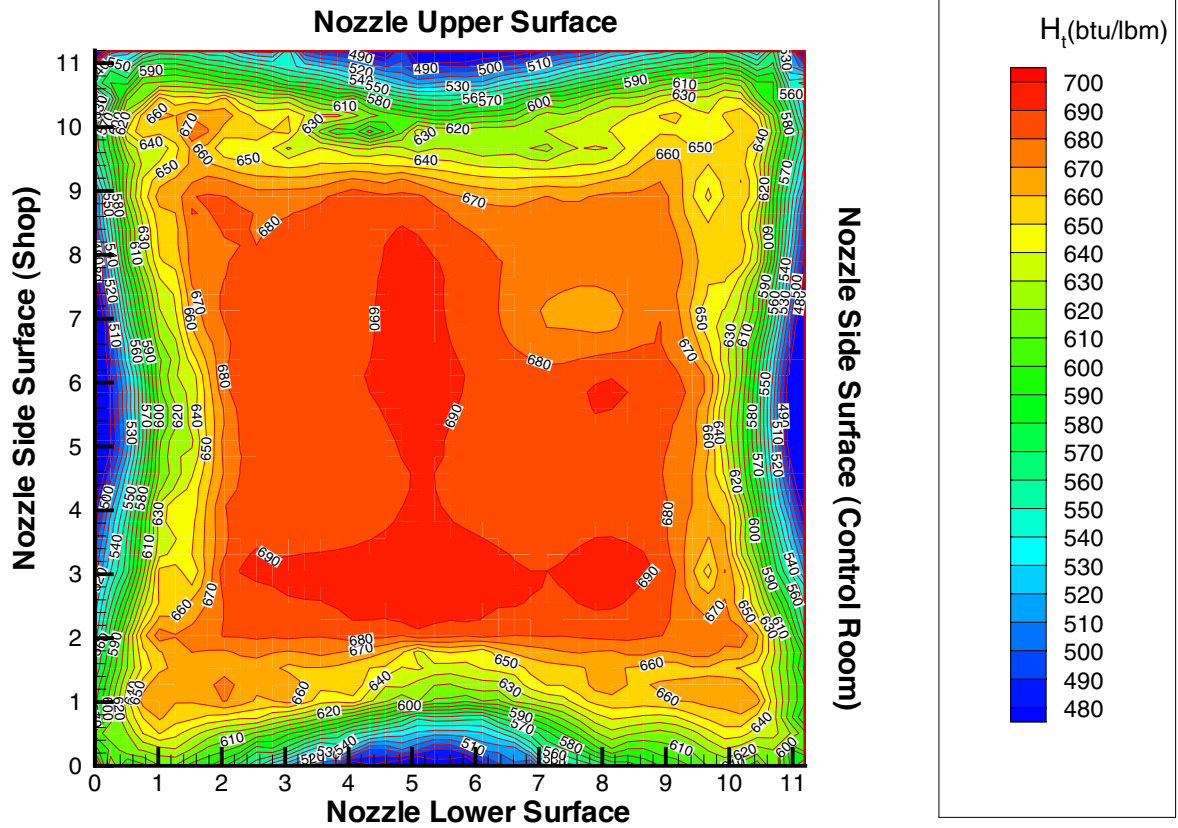


Figure 13d. Total enthalpy contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

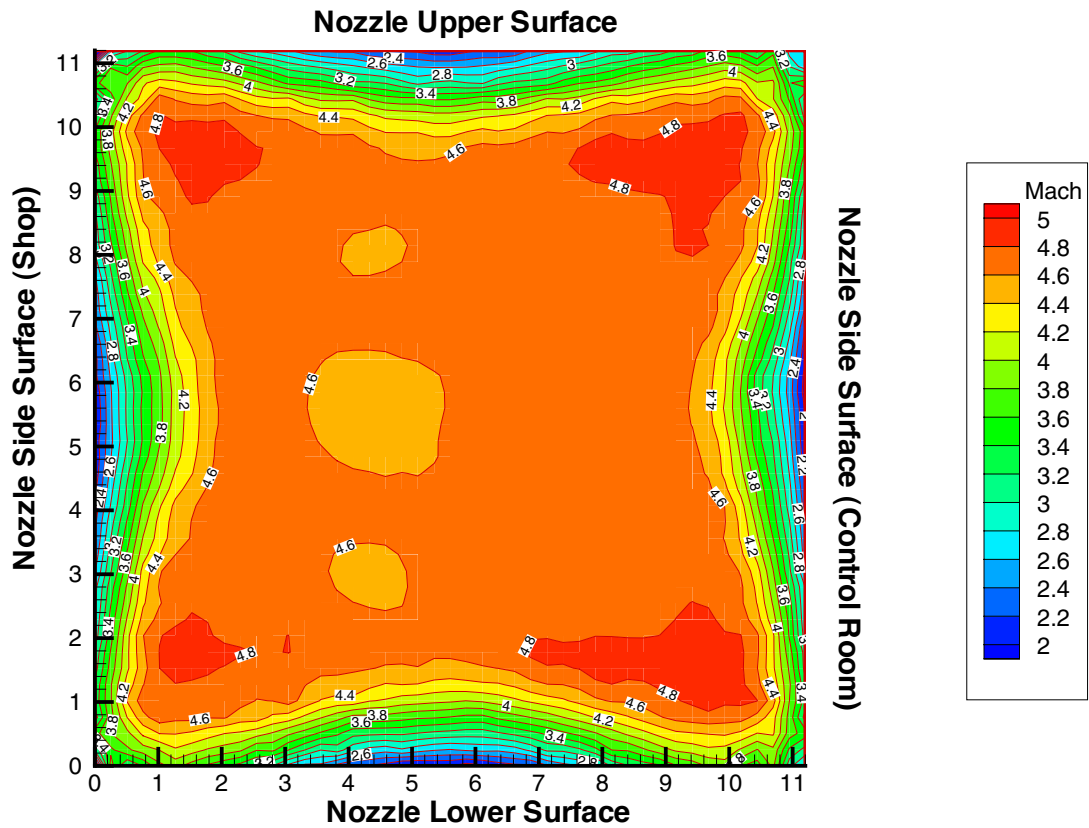


Figure 13e. Mach contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

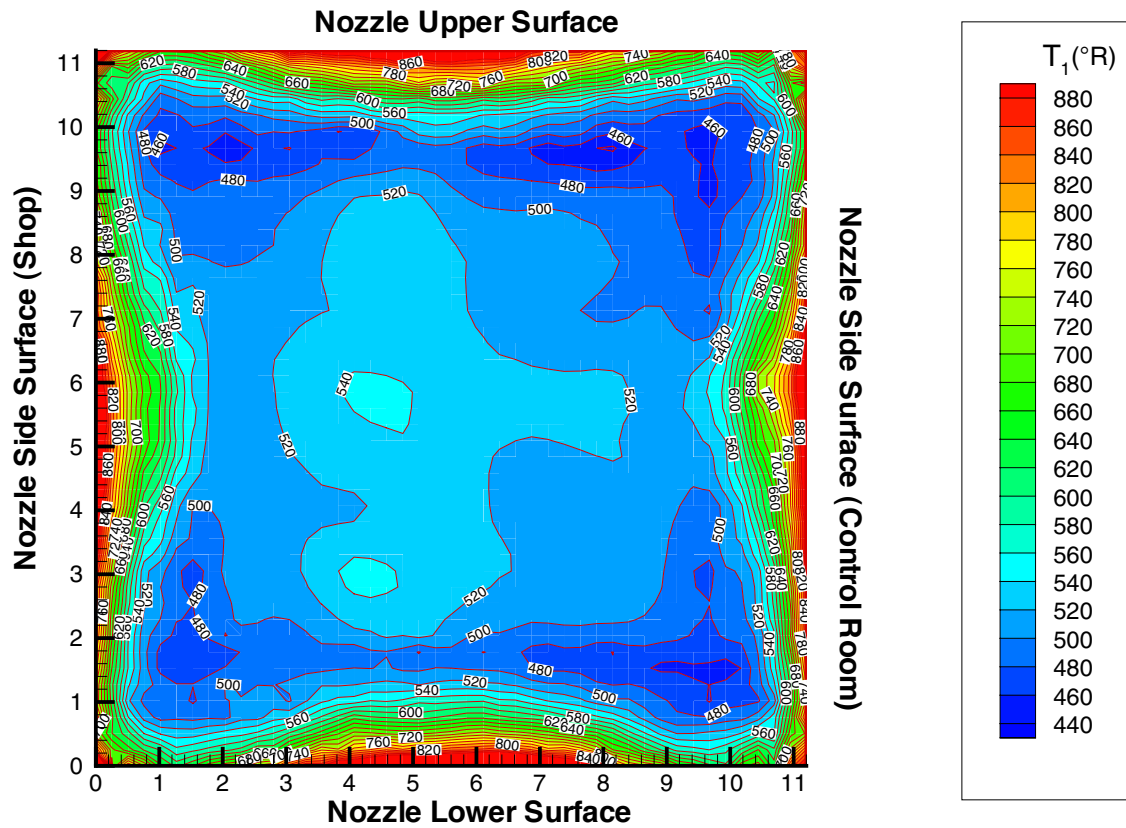


Figure 13f. Static temperature contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point ($PT1 = 180$ psia, $HST = 690$ btu/lbm). All dimensions are in inches.

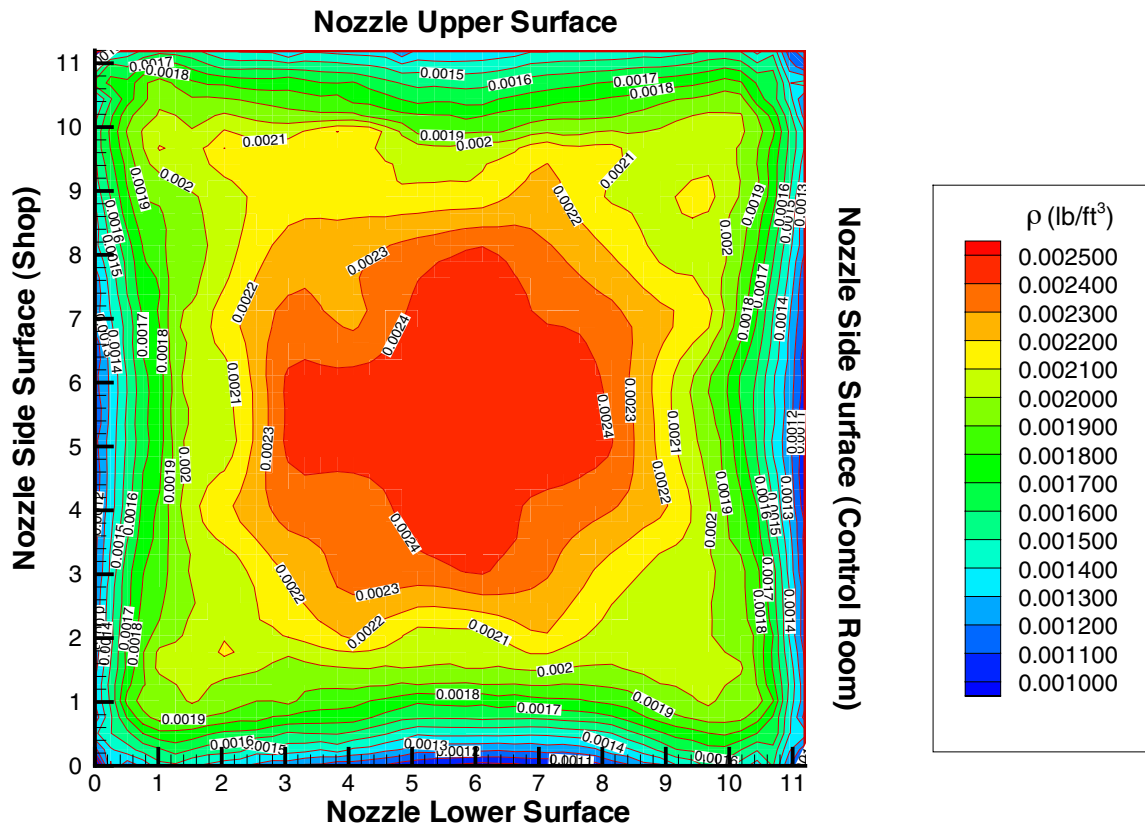


Figure 13g. Static density contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

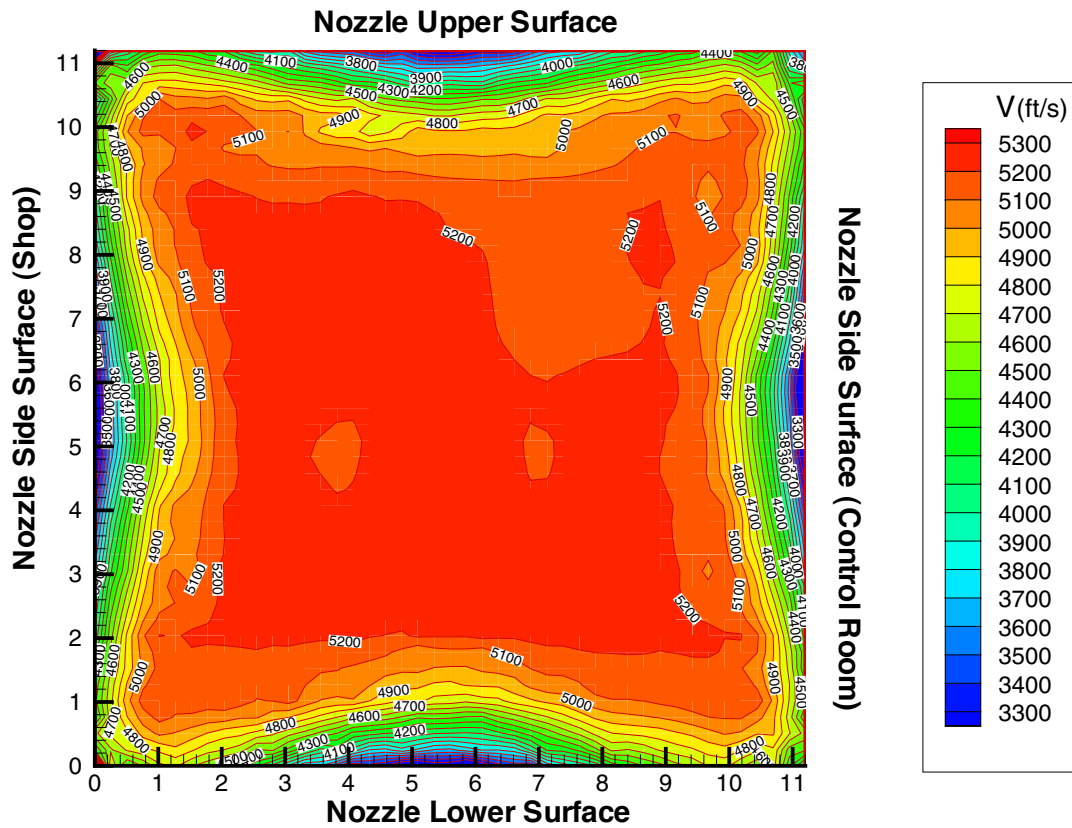


Figure 13h. Velocity contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

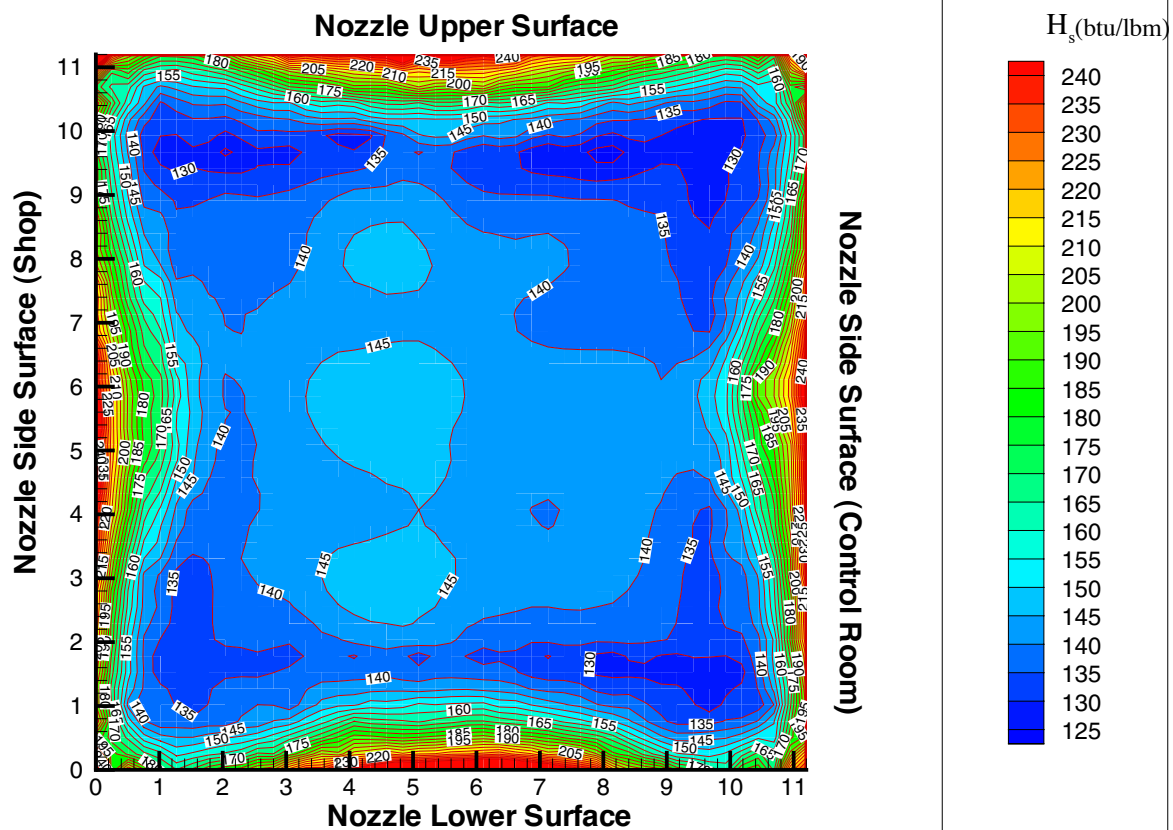


Figure 13i. Static enthalpy contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

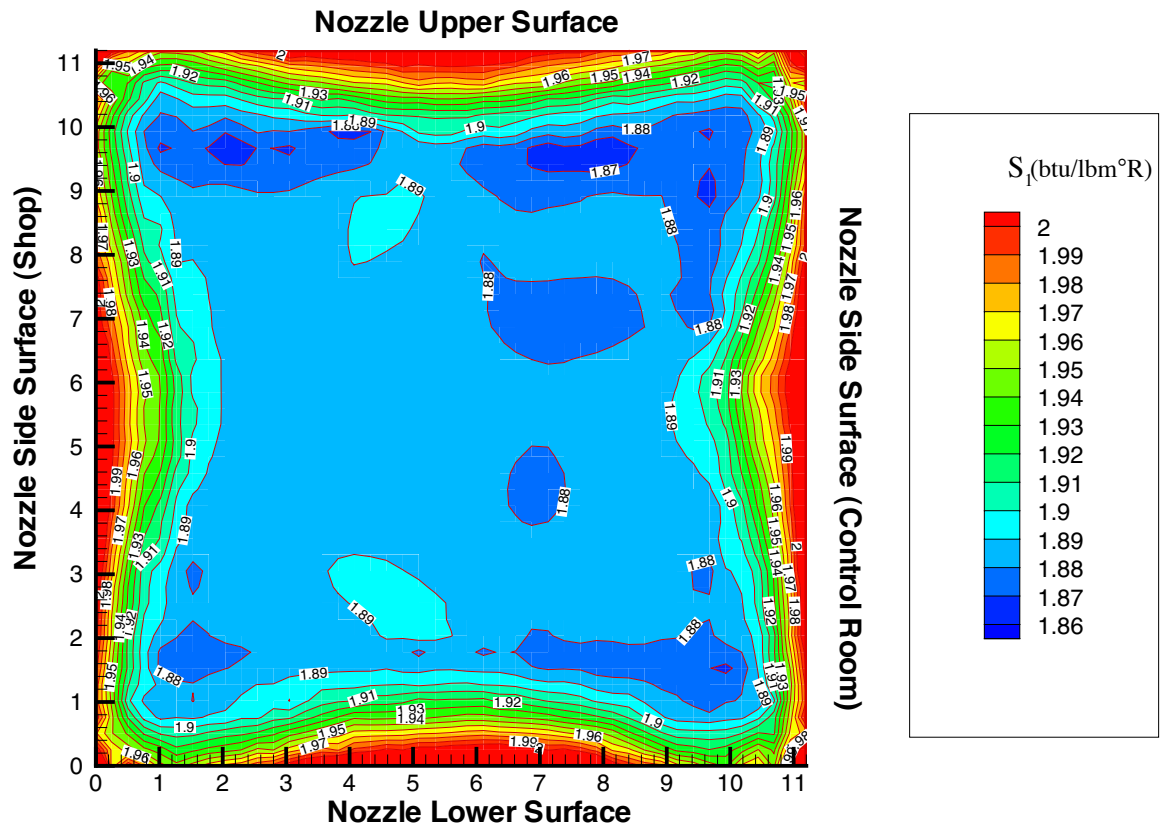


Figure 13j. Entropy contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

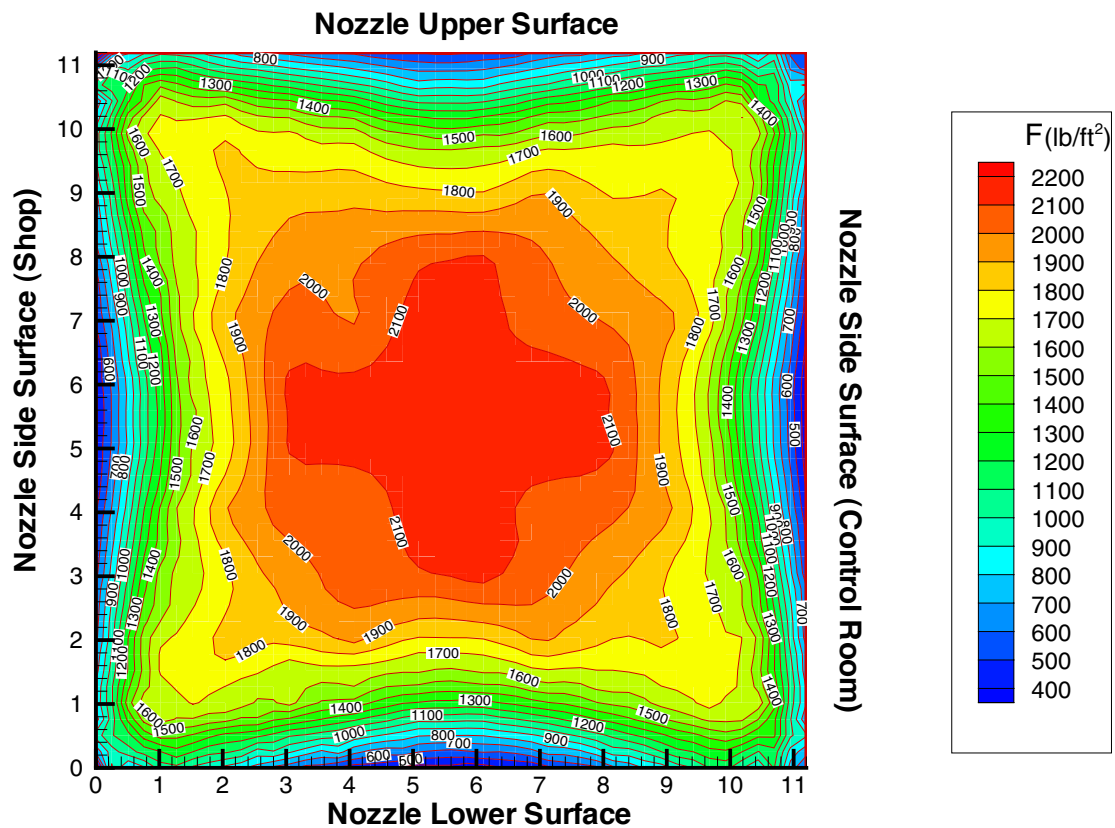


Figure 13k. Stream thrust contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

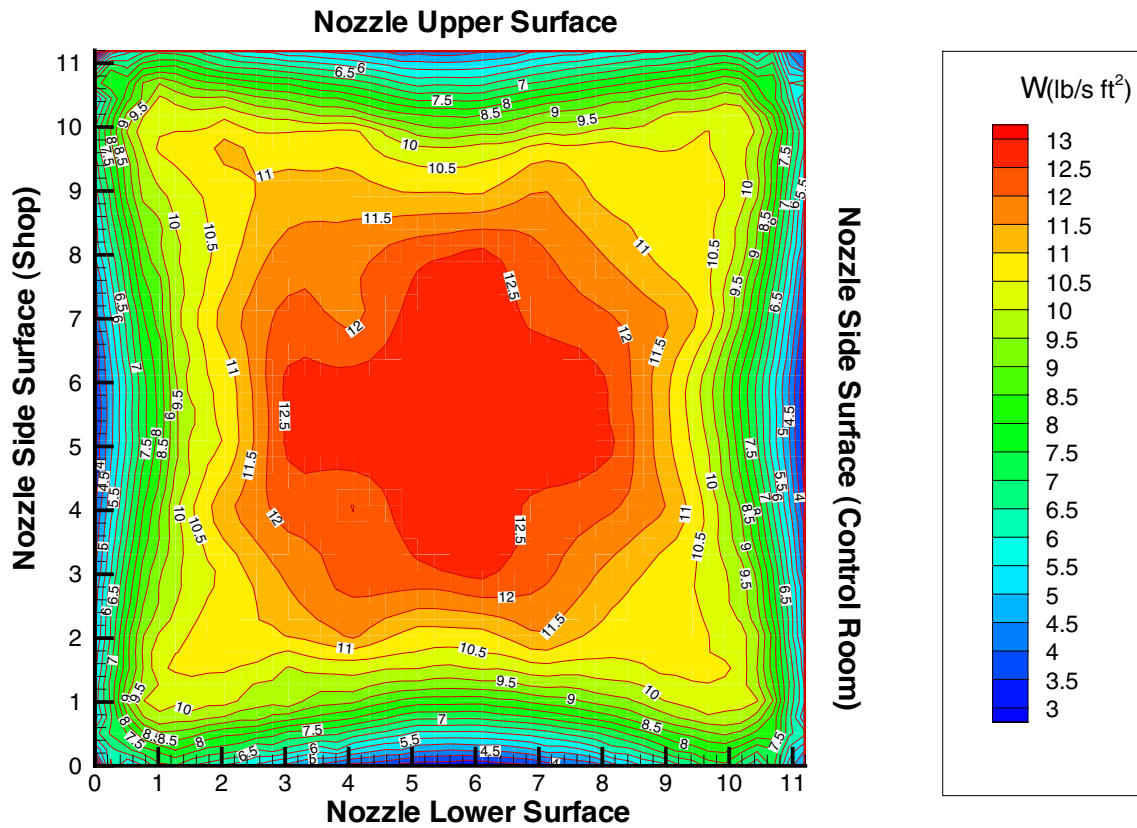


Figure 13l. Mass flux contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

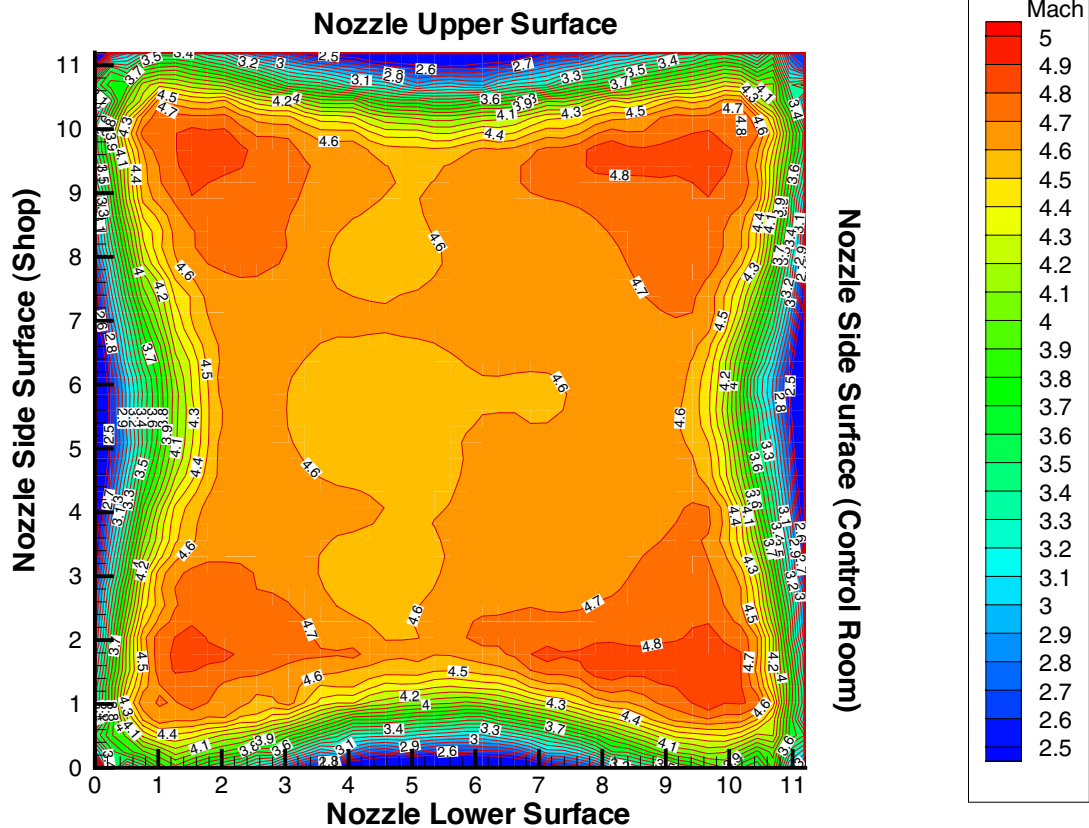


Figure 13m. Mach contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

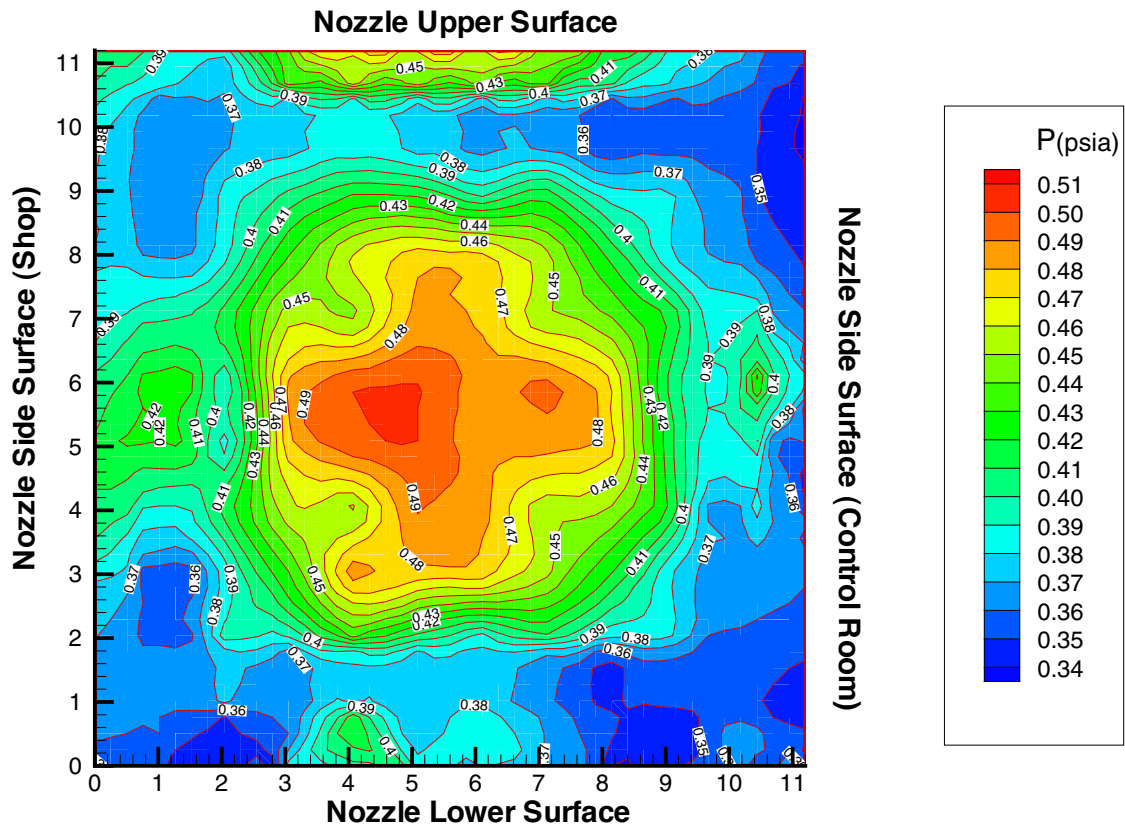


Figure 13n. Static pressure contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point ($PT1 = 180$ psia, $HST = 690$ btu/lbm). All dimensions are in inches.

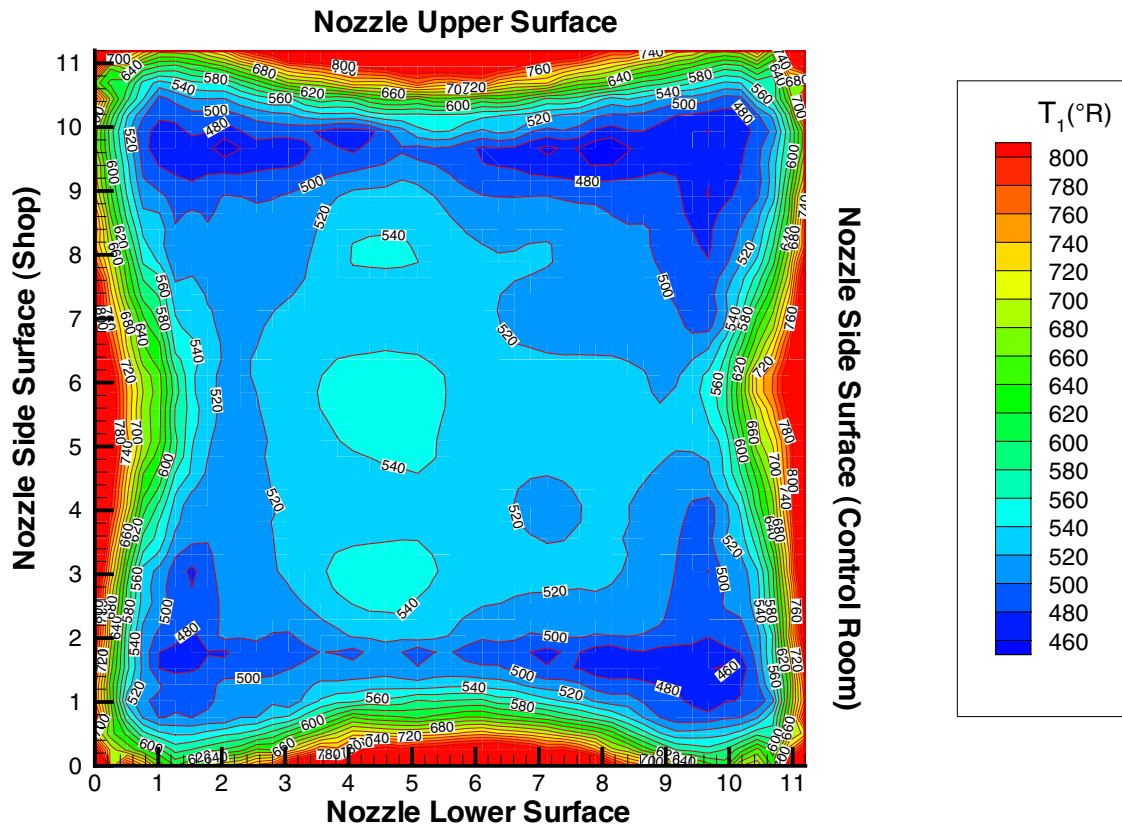


Figure 13o. Static temperature contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point ($PT_1 = 180$ psia, $HST = 690$ btu/lbm). All dimensions are in inches.

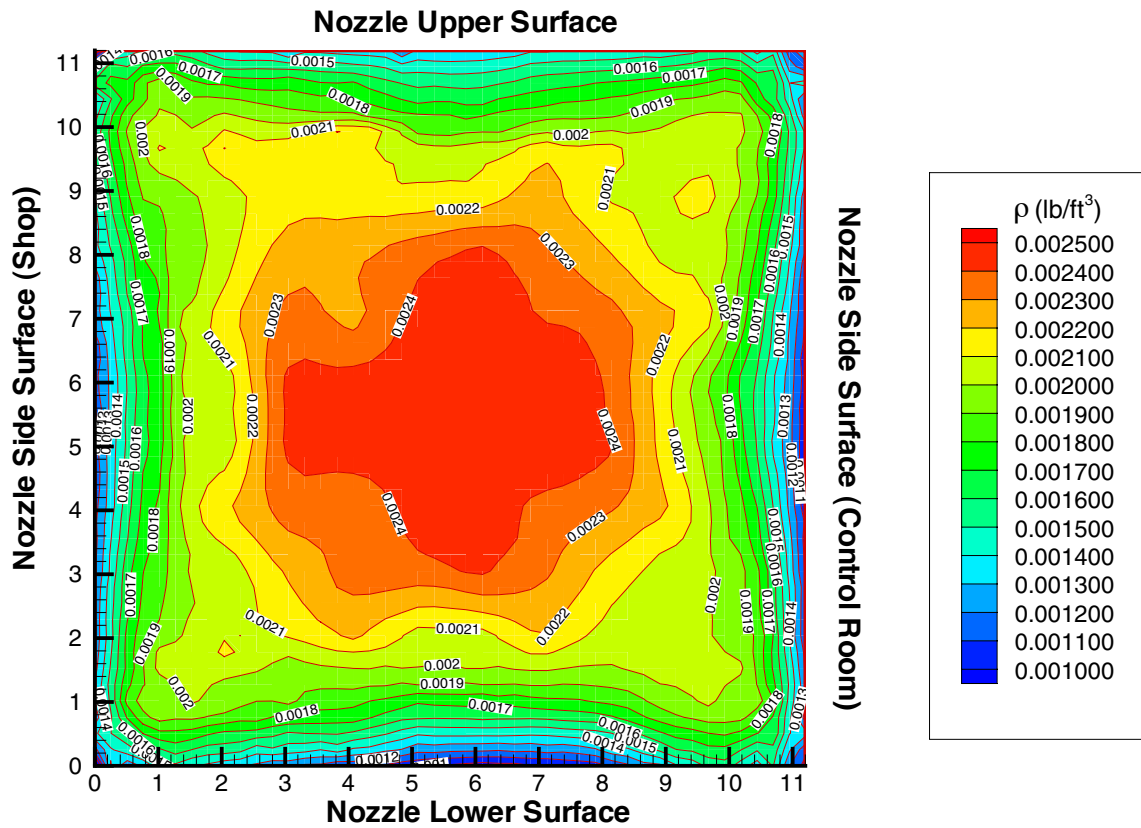


Figure 13p. Static density contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

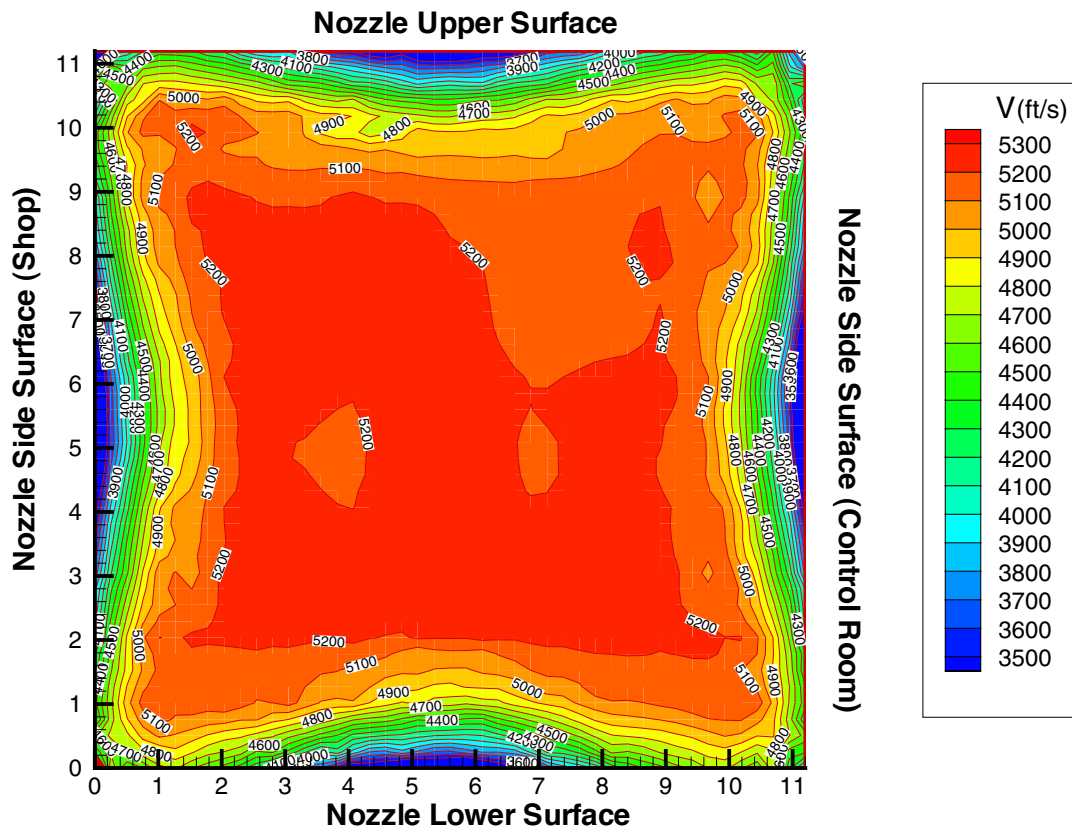


Figure 13q. Velocity contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

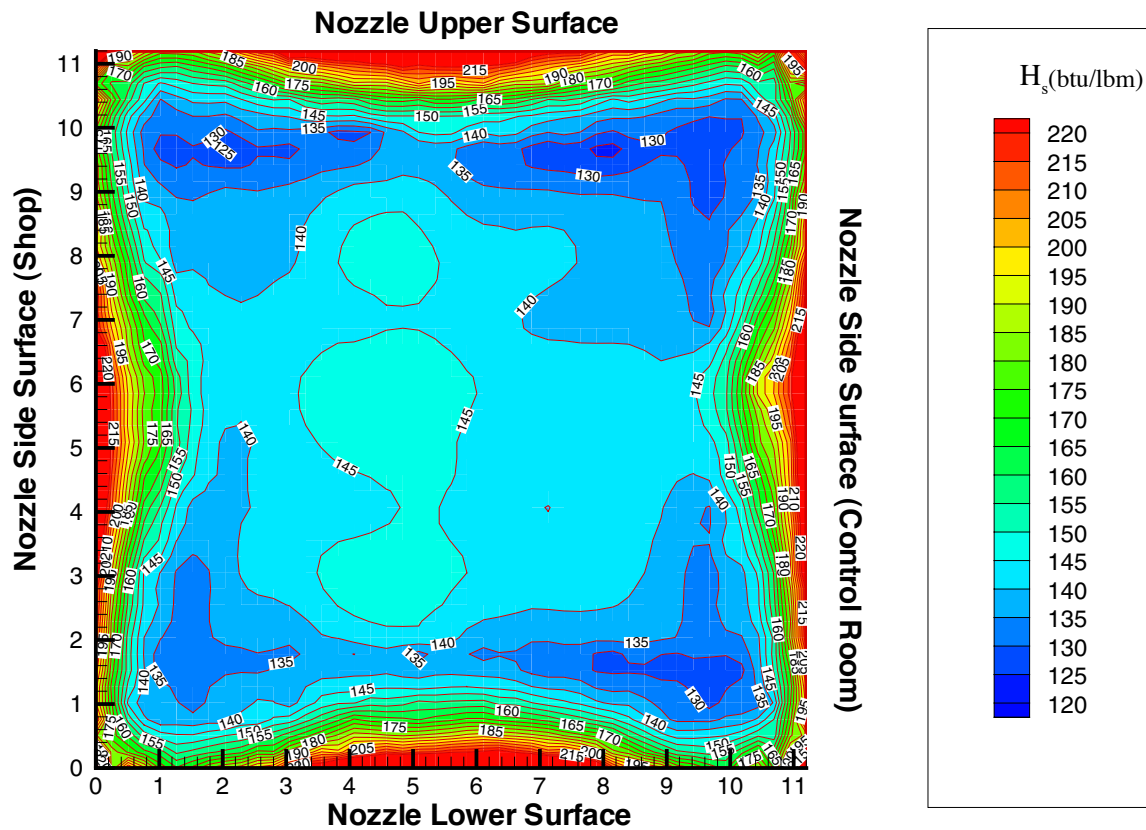


Figure 13r. Static enthalpy contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

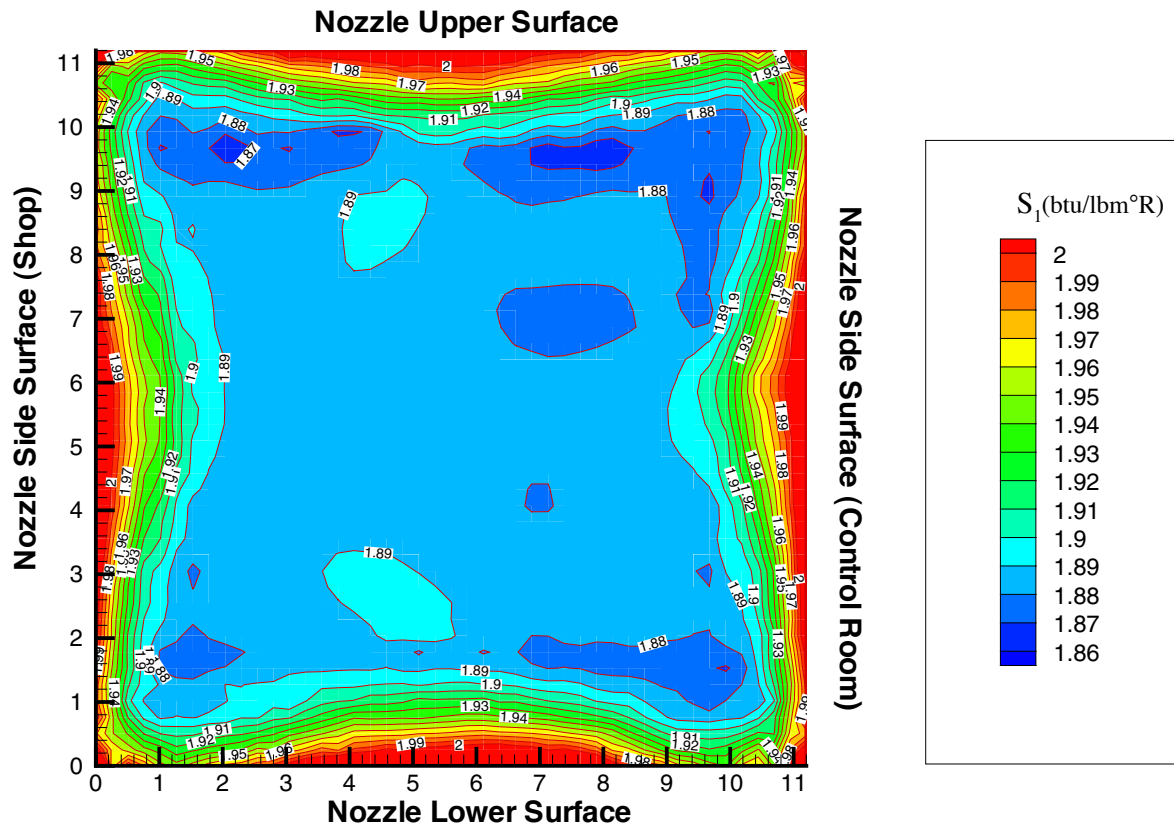


Figure 13s. Entropy contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

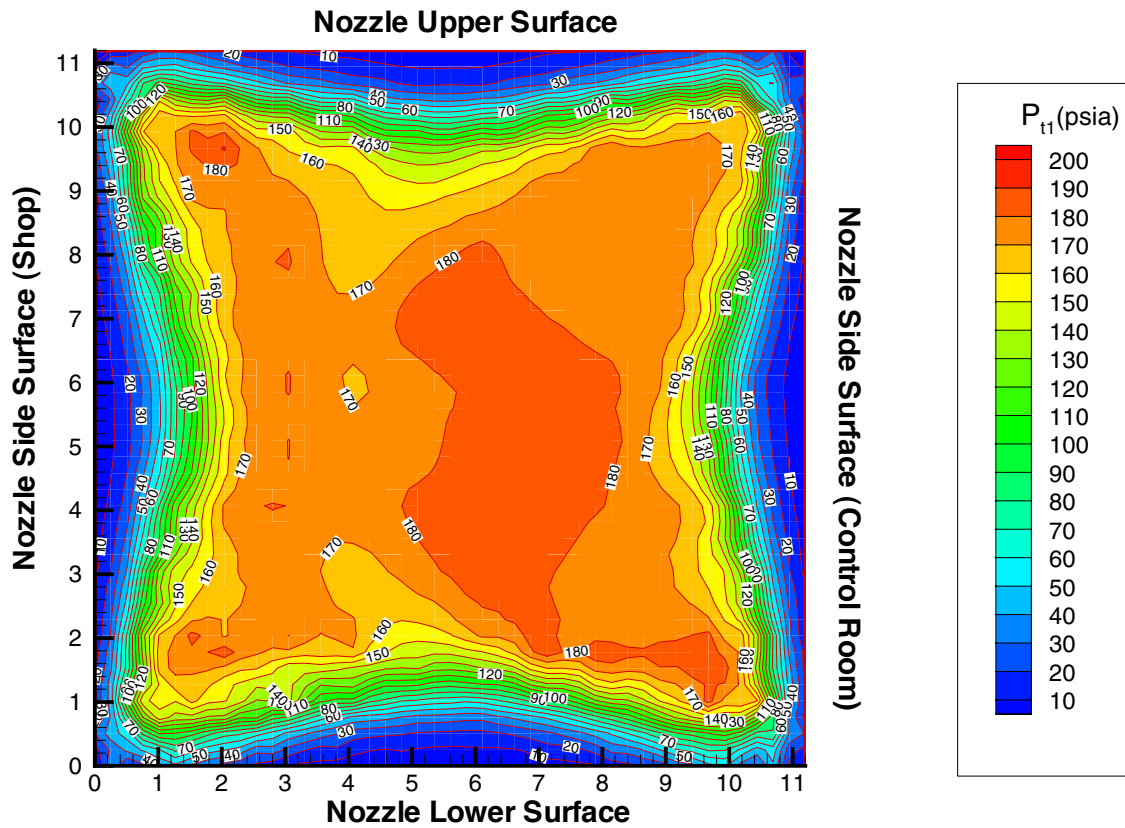


Figure 13t. Freestream total pressure contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point ($P_{t1} = 180$ psia, $HST = 690$ btu/lbm). All dimensions are in inches.

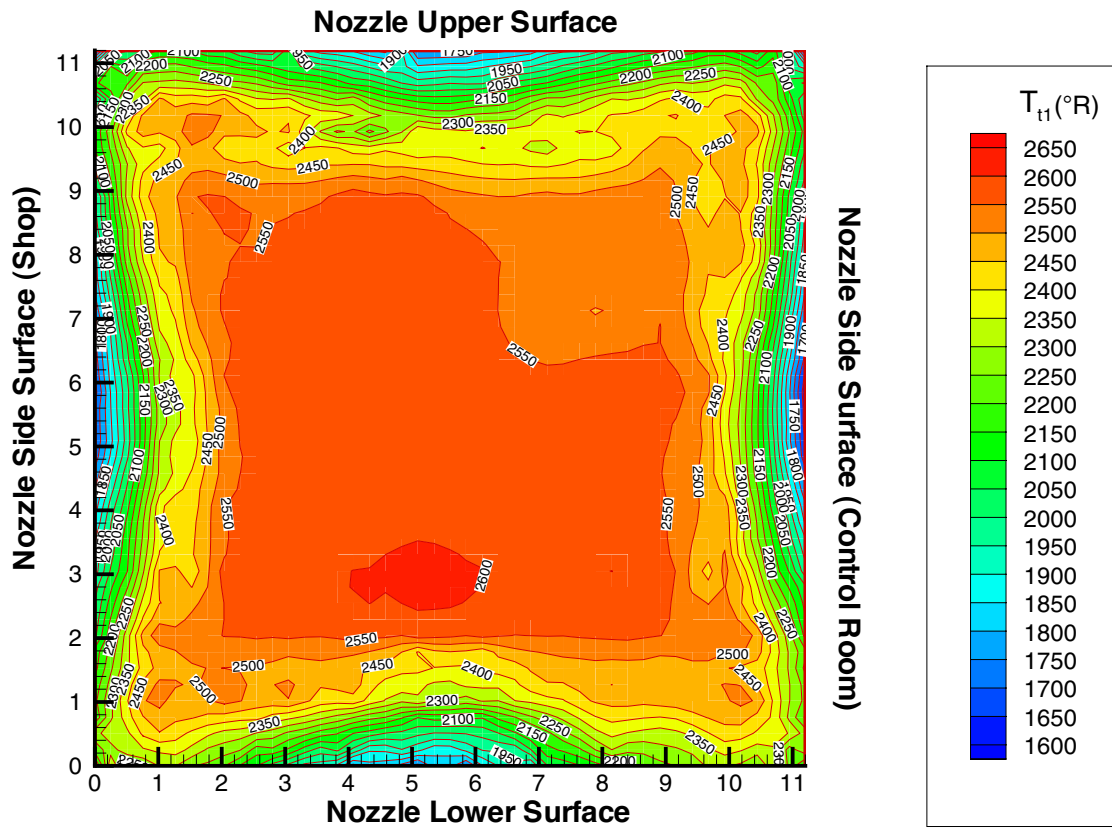


Figure 13u. Freestream total temperature contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

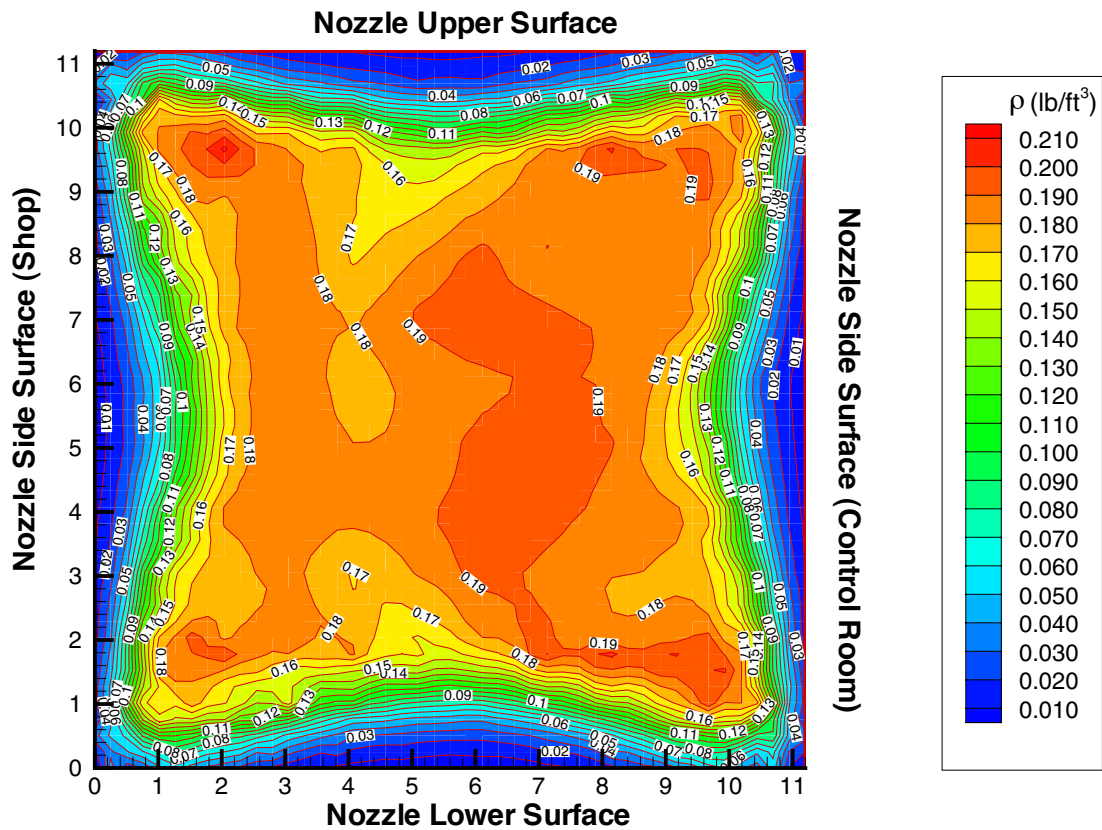


Figure 13v. Freestream total density contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5.5 enthalpy test point (PT1 = 180 psia, HST = 690 btu/lbm). All dimensions are in inches.

Mach 4.7 Nozzle, Mach 5 Enthalpy, Delta Pressure Test Condition

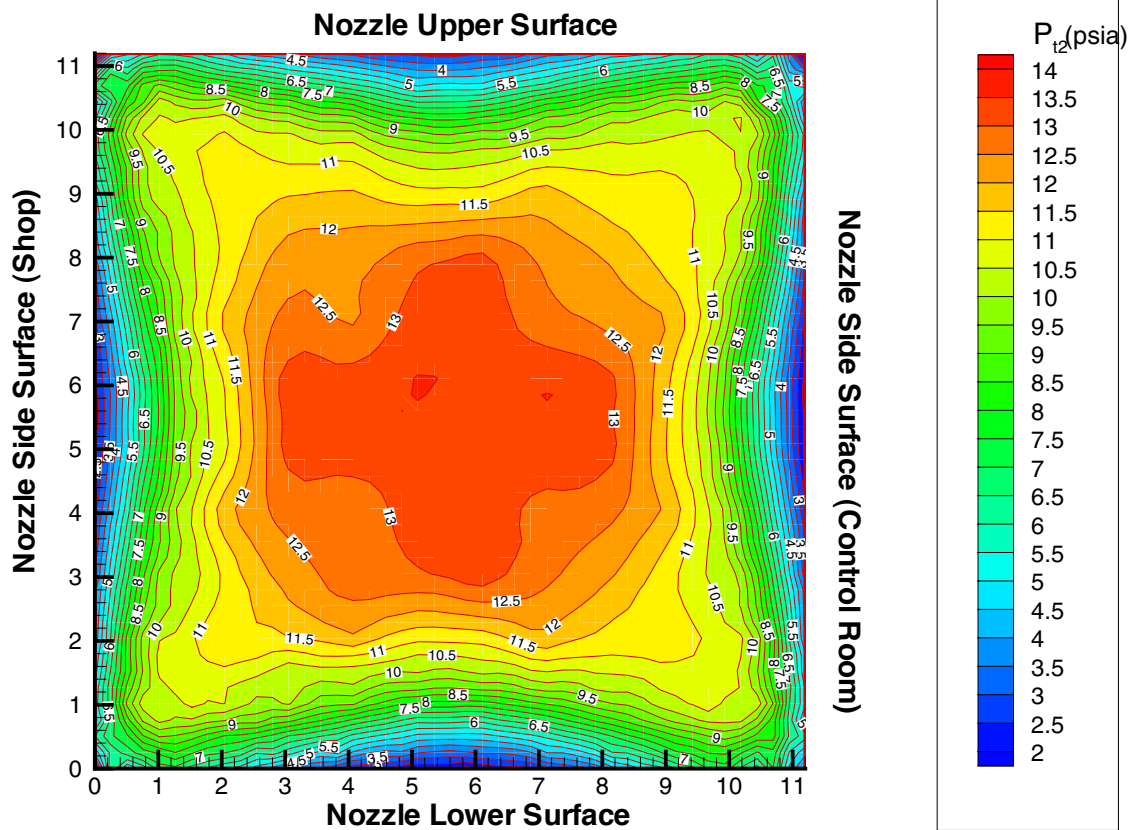


Figure 14a. Pitot pressure contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

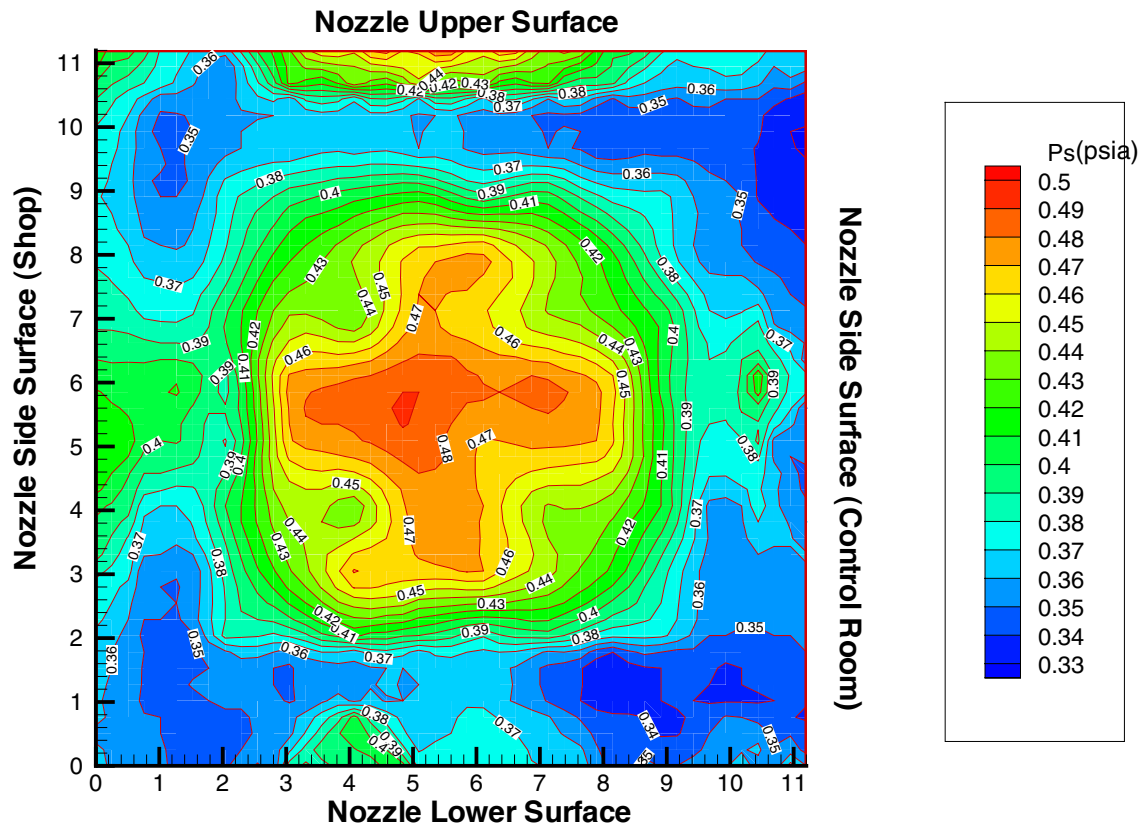


Figure 14b. Static pressure contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

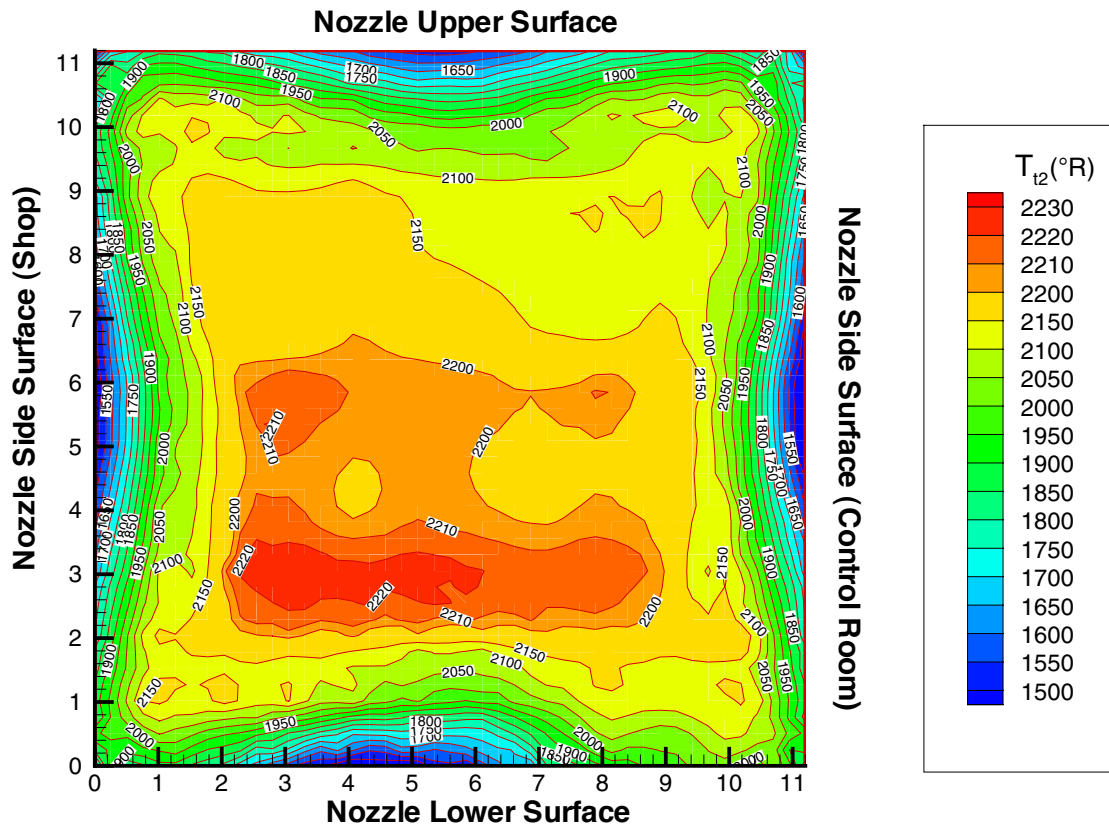


Figure 14c. Total temperature contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

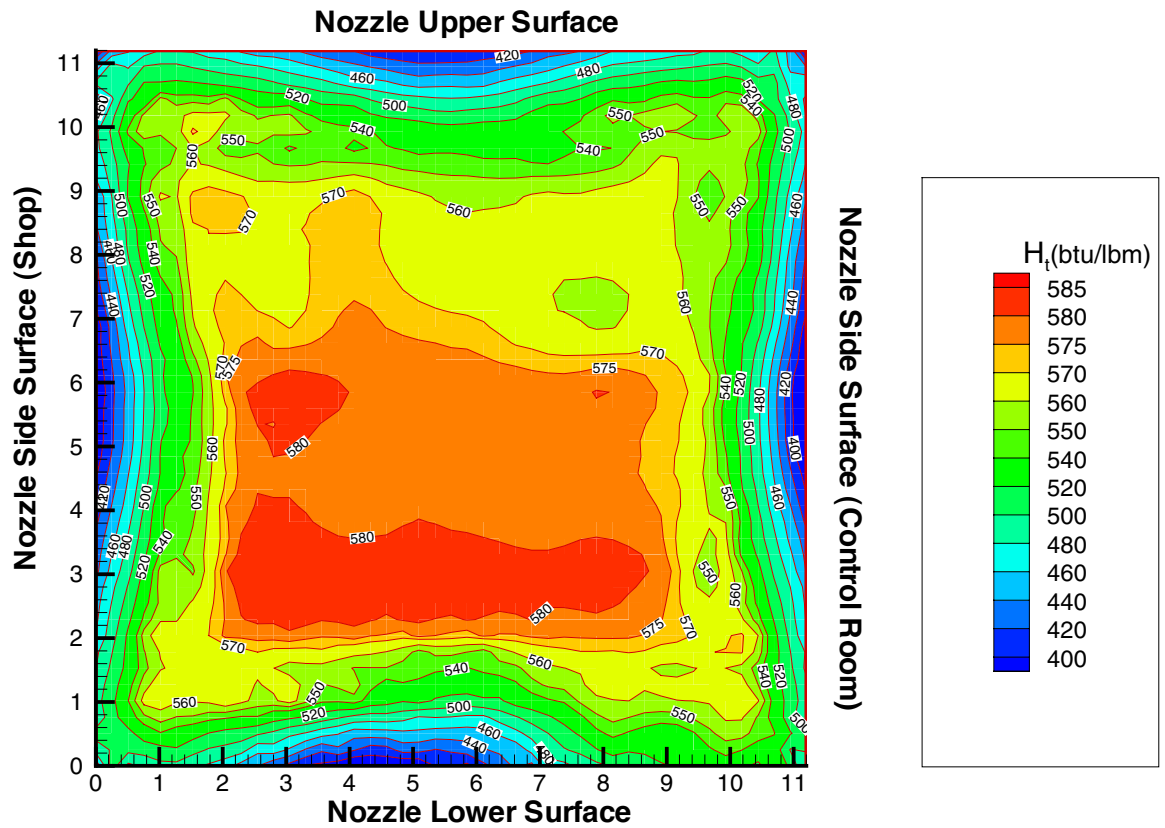


Figure 14d. Total enthalpy contours (measured) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

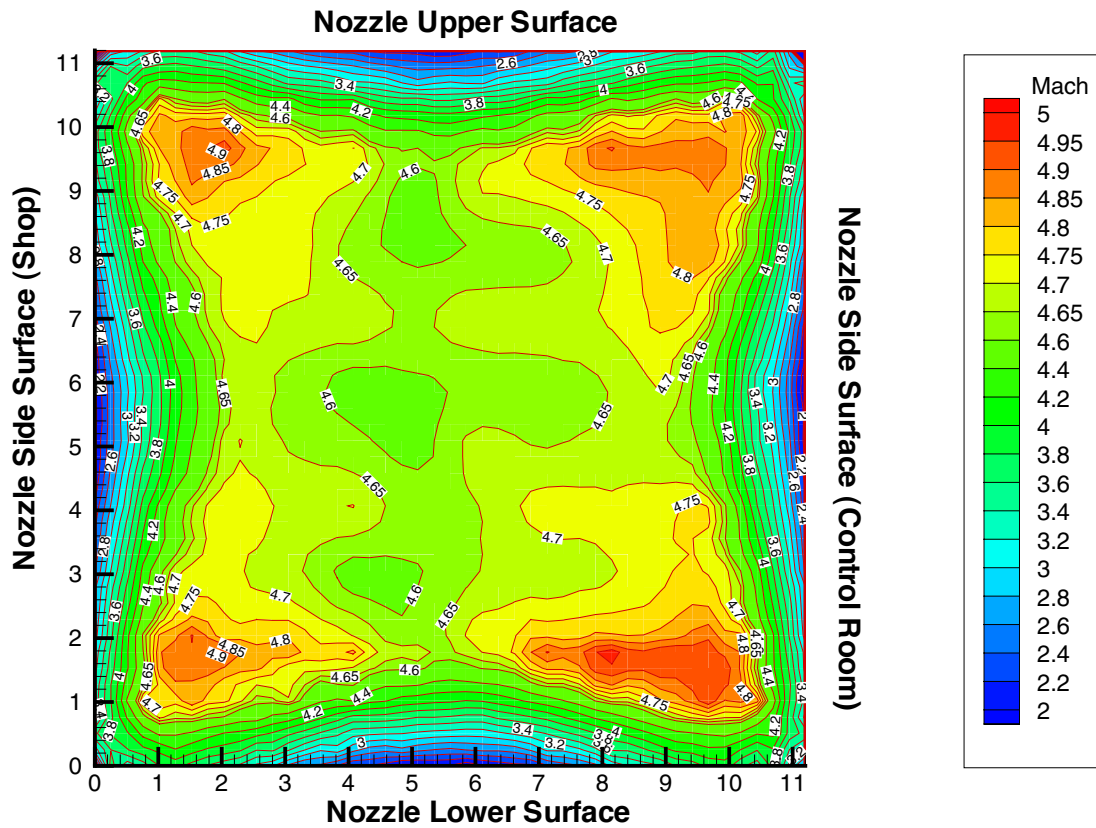


Figure 14e. Mach contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

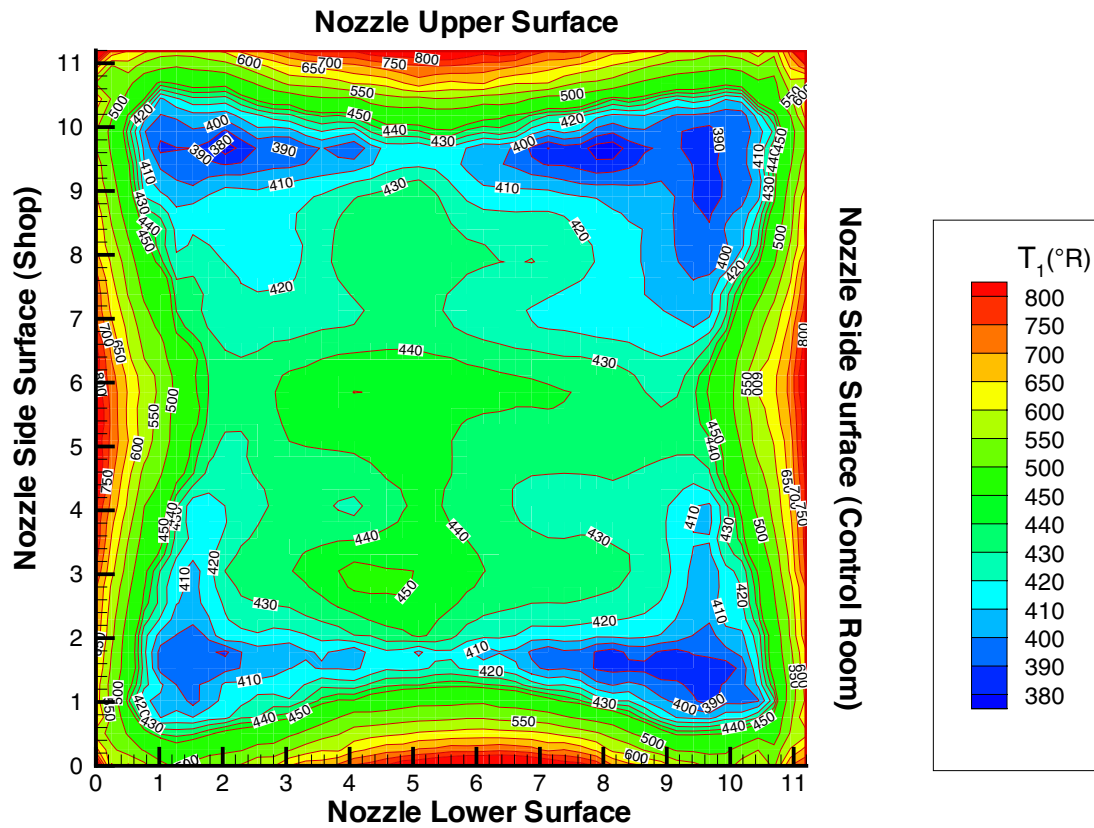


Figure 14f. Static temperature contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

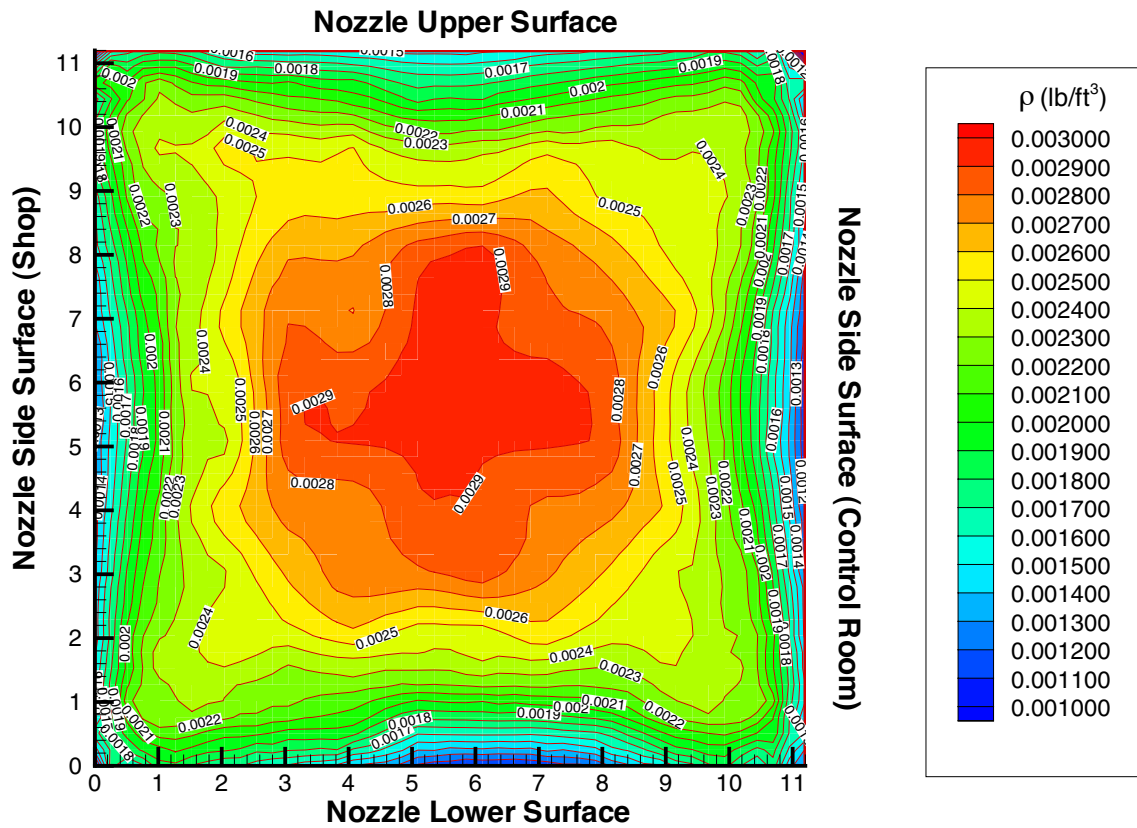


Figure 14g. Static density contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

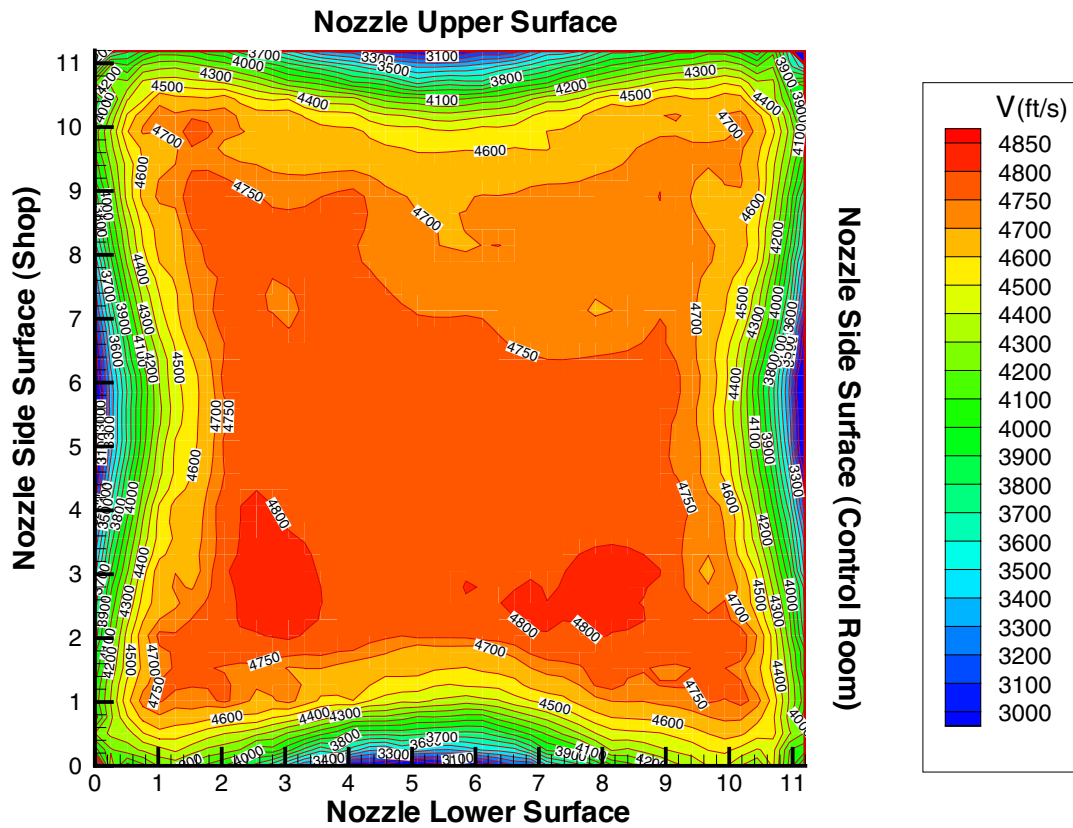


Figure 14h. Velocity contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

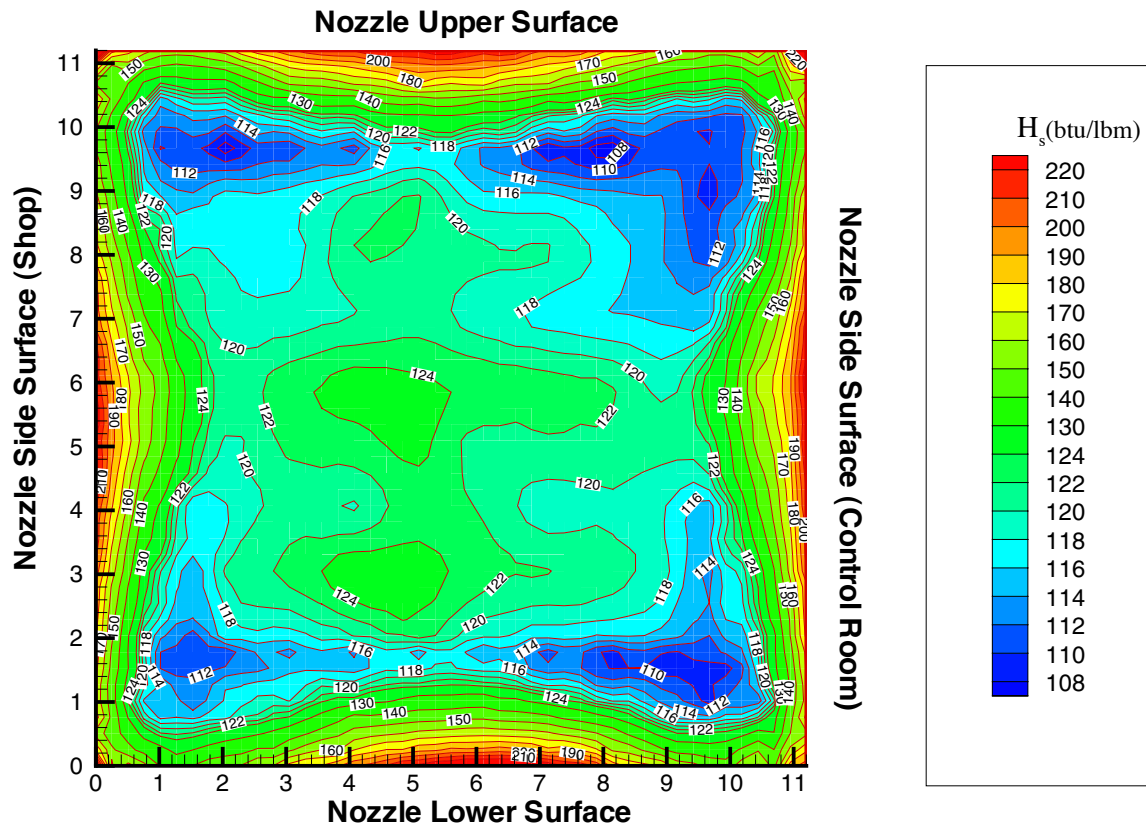


Figure 14i. Static enthalpy contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

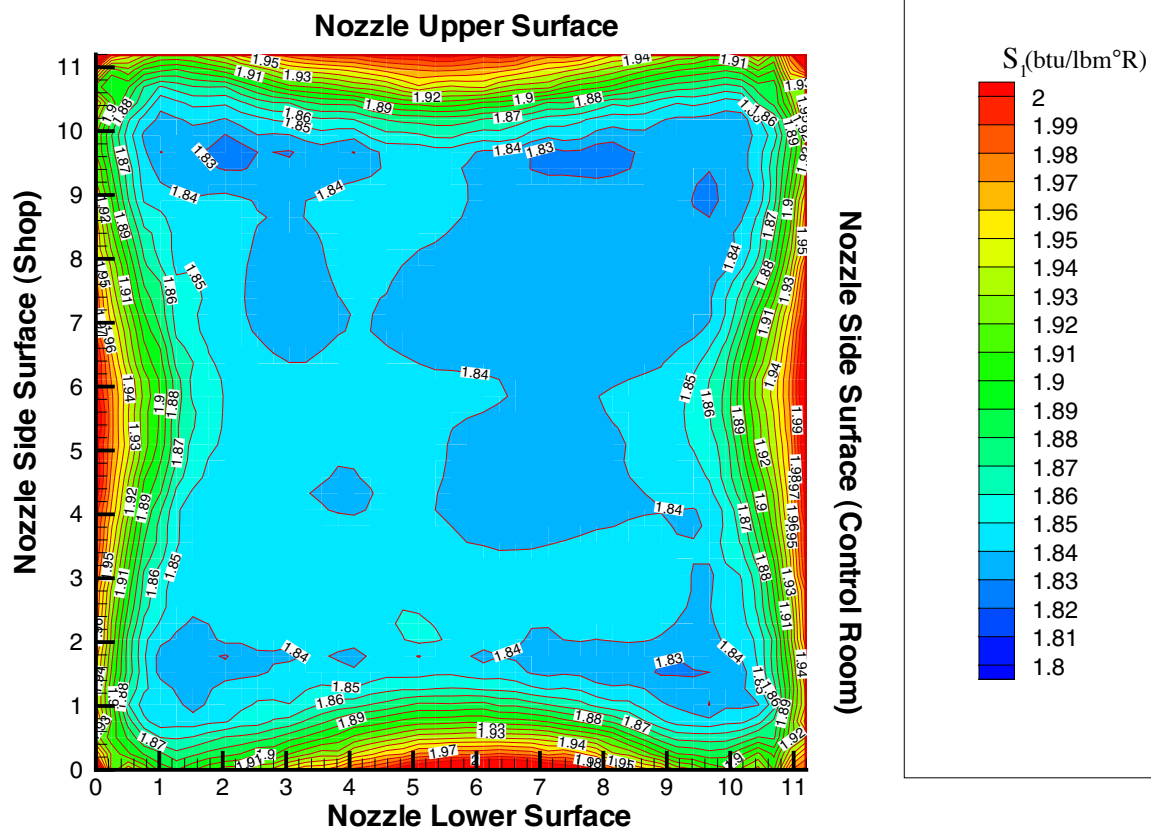


Figure 14j. Entropy contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

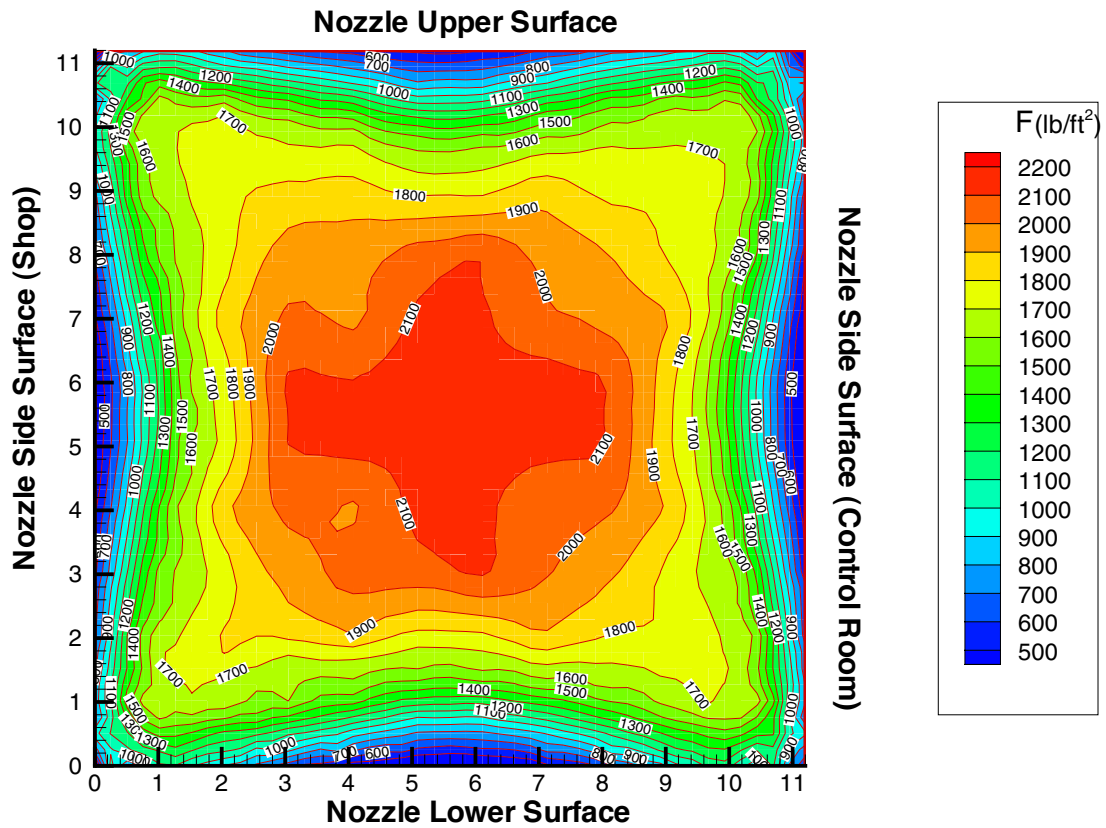


Figure 14k. Stream thrust contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

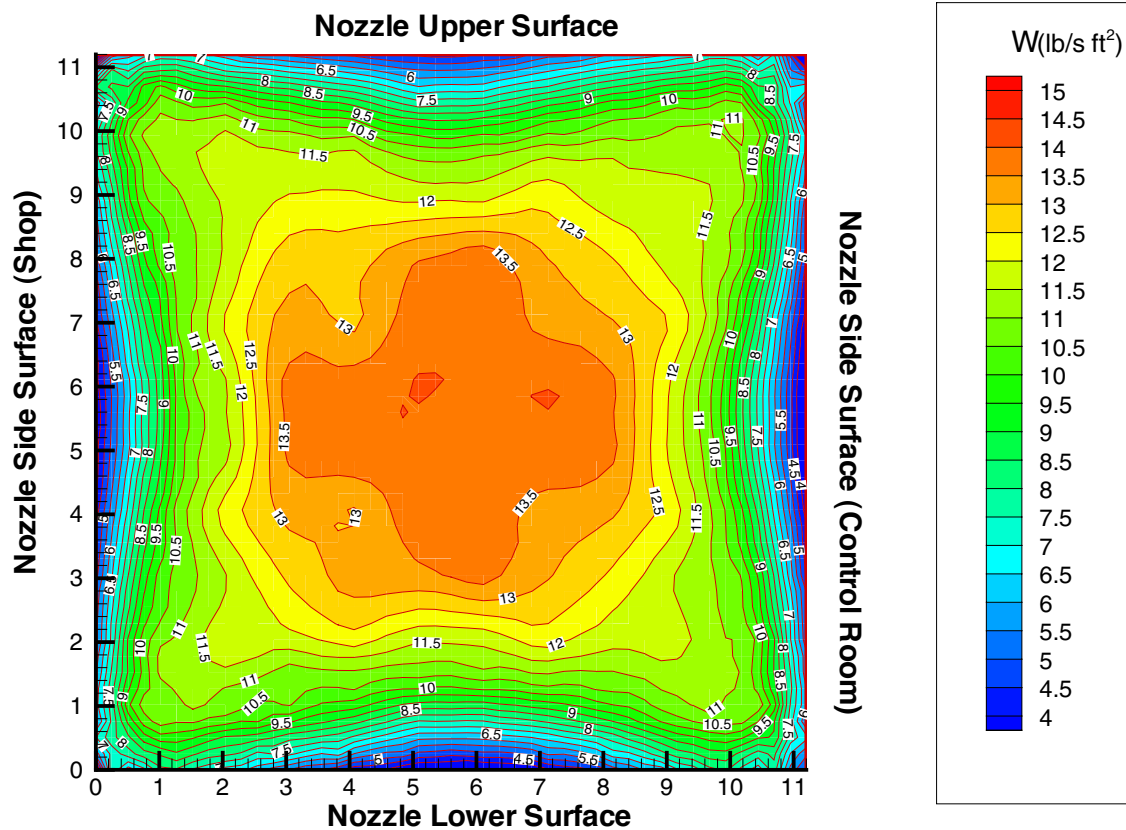


Figure 14l. Mass flux contours (vibrationally frozen) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

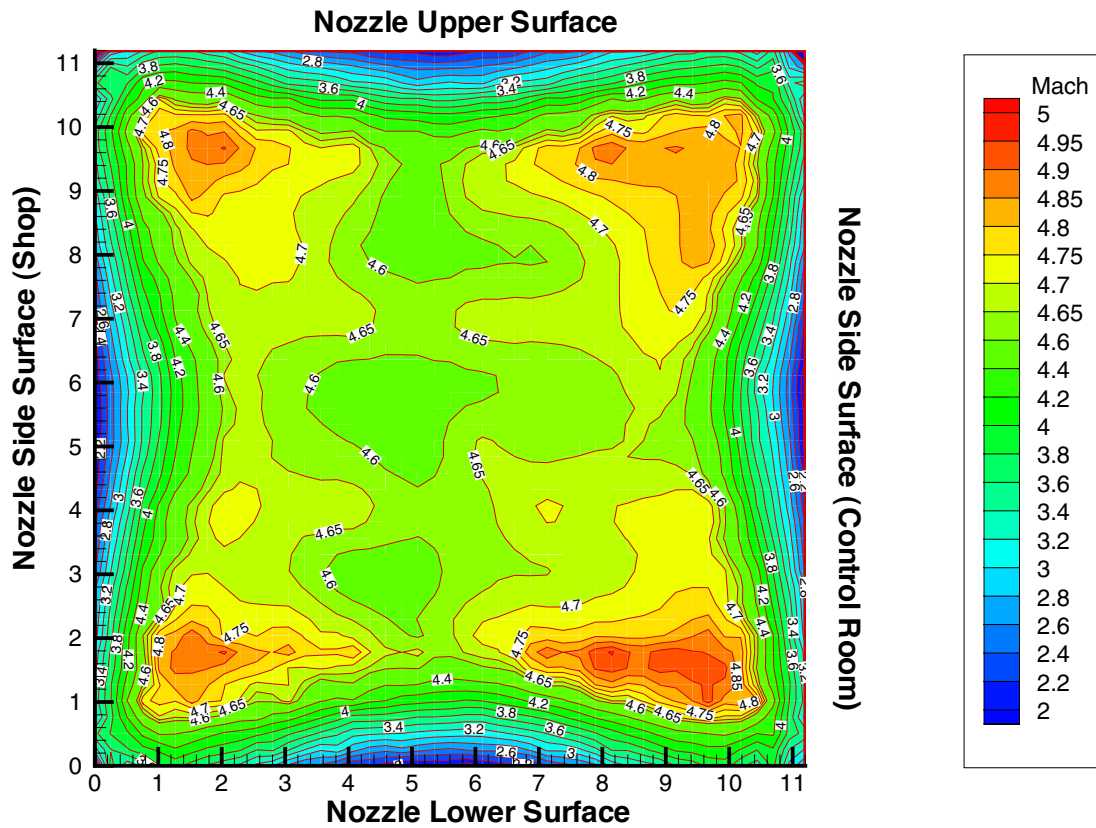


Figure 14m. Mach contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

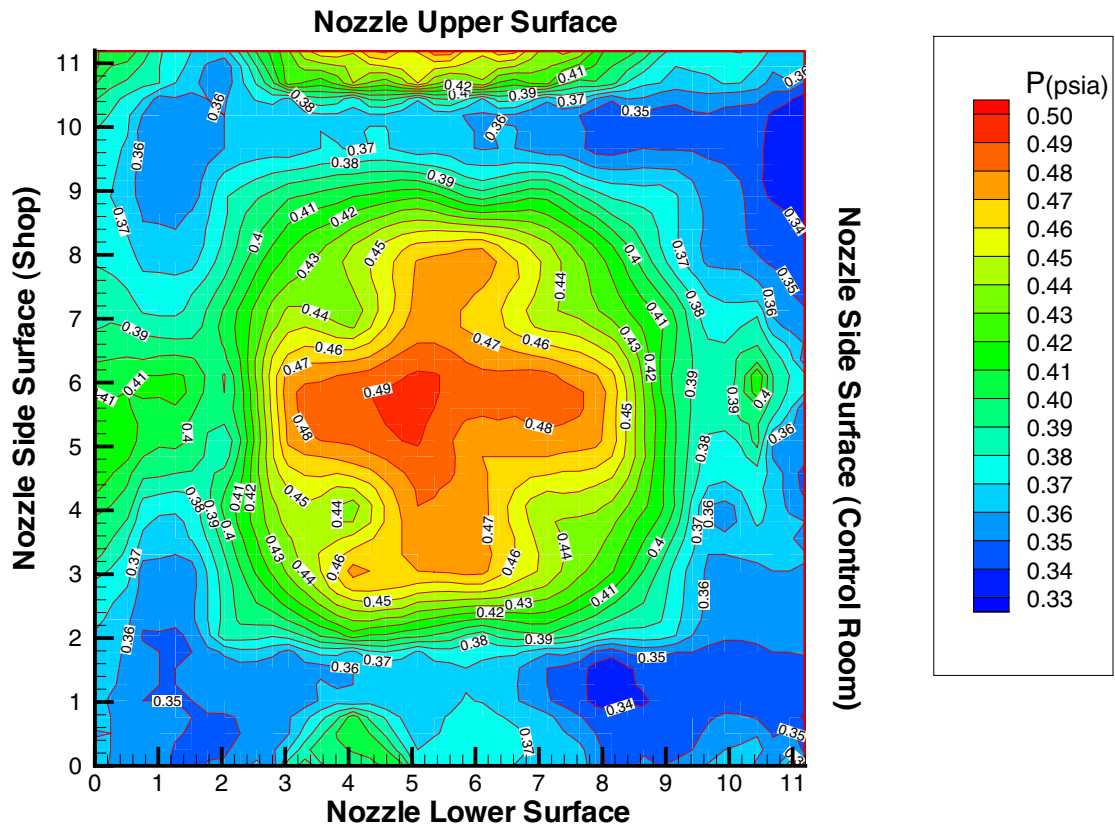


Figure 14n. Static pressure contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

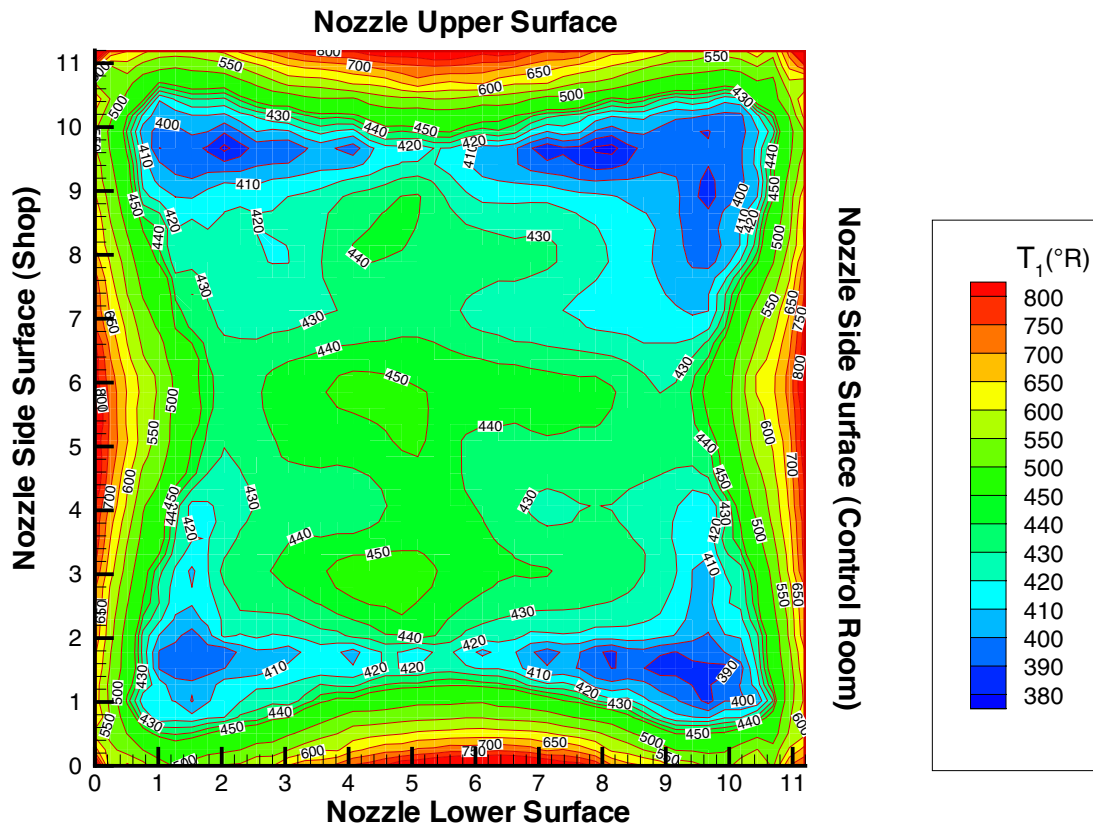


Figure 14o. Static temperature contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

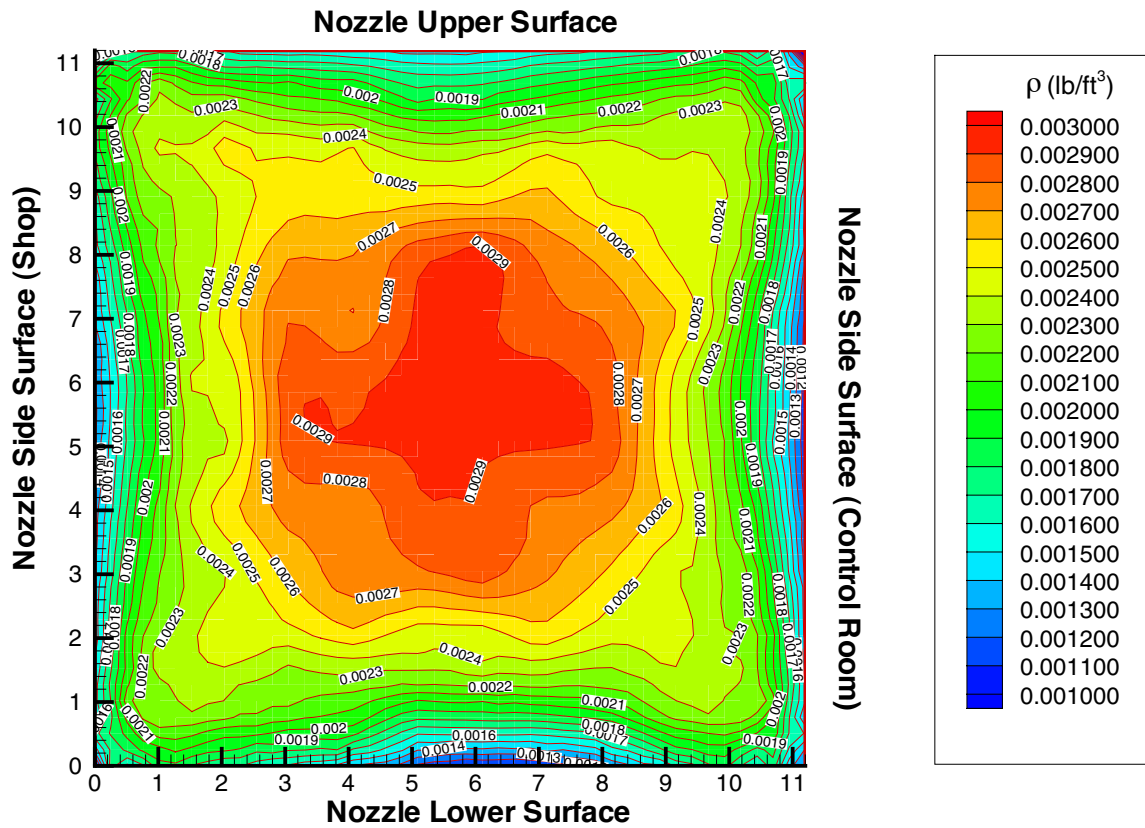


Figure 14p. Static density contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

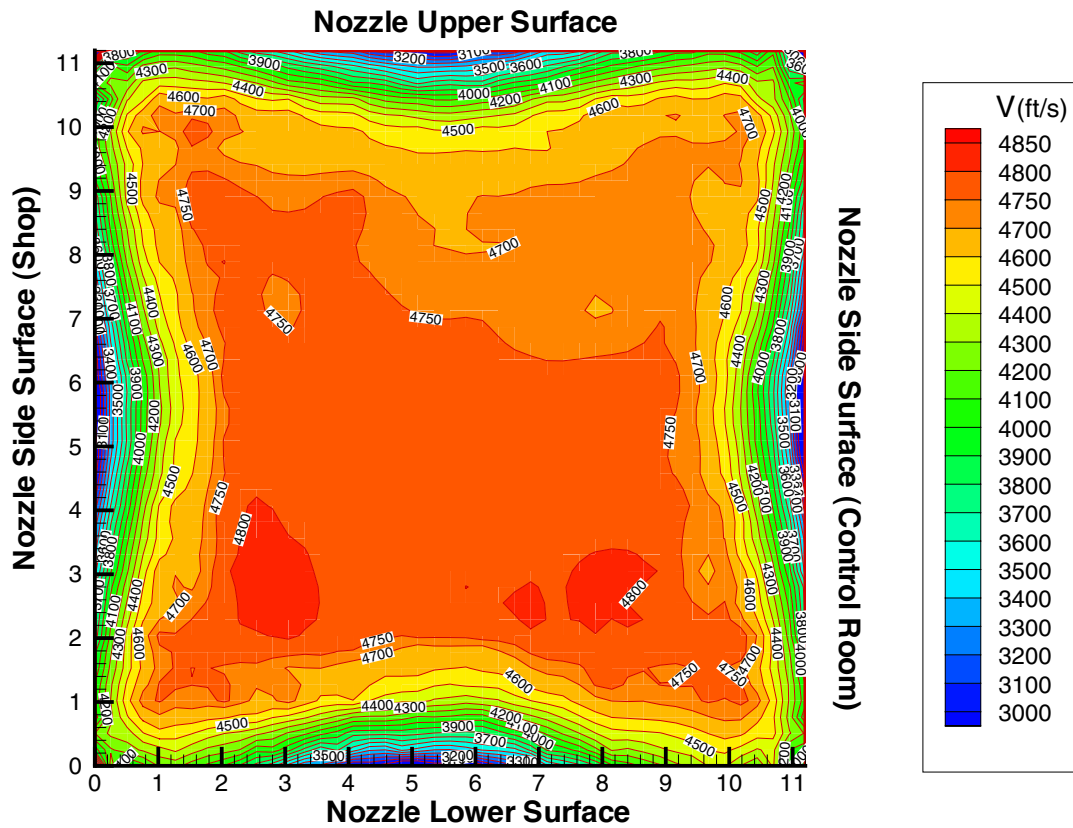


Figure 14q. Velocity contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

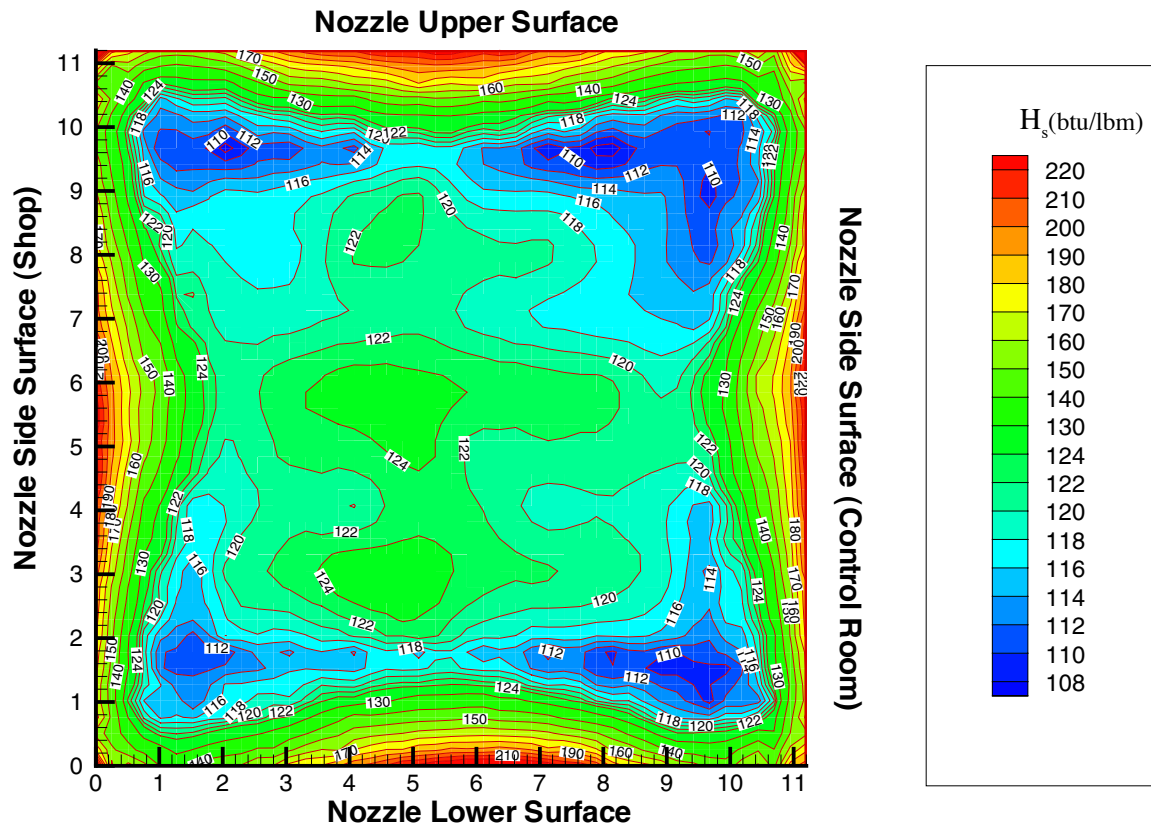


Figure 14r. Static enthalpy contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

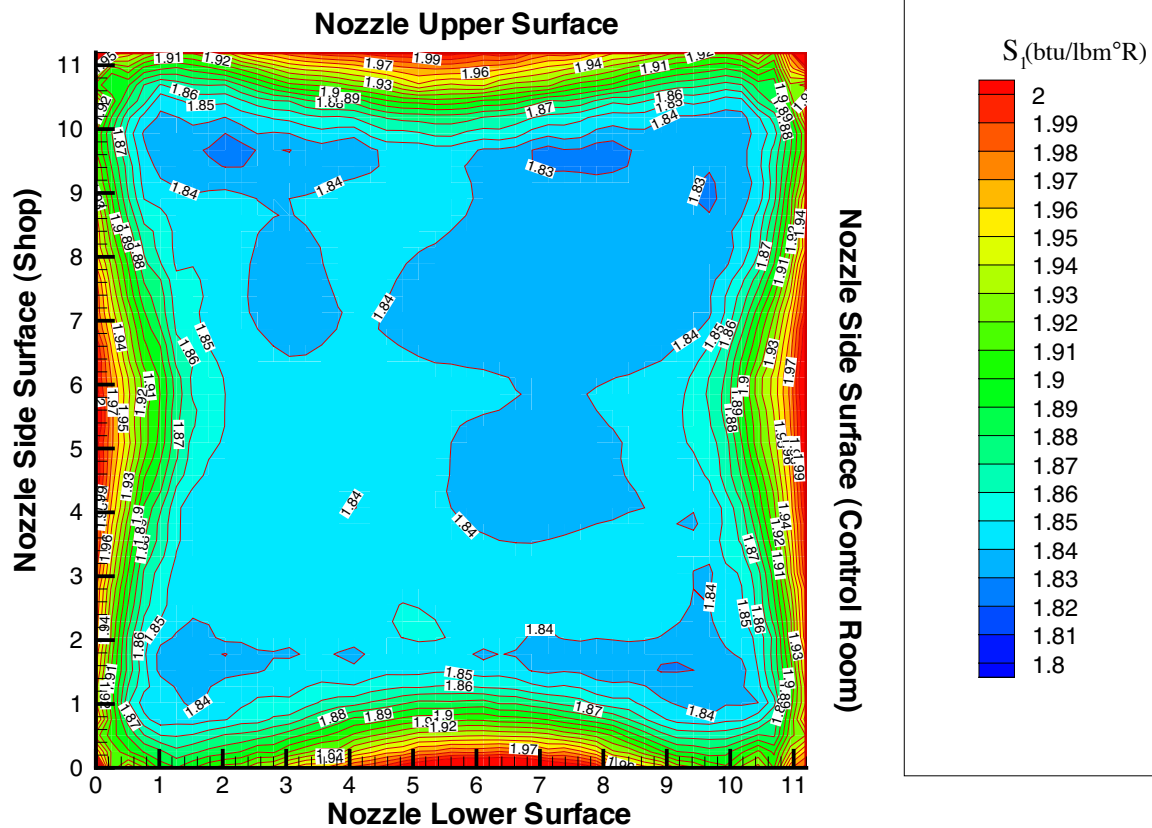


Figure 14s. Entropy contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

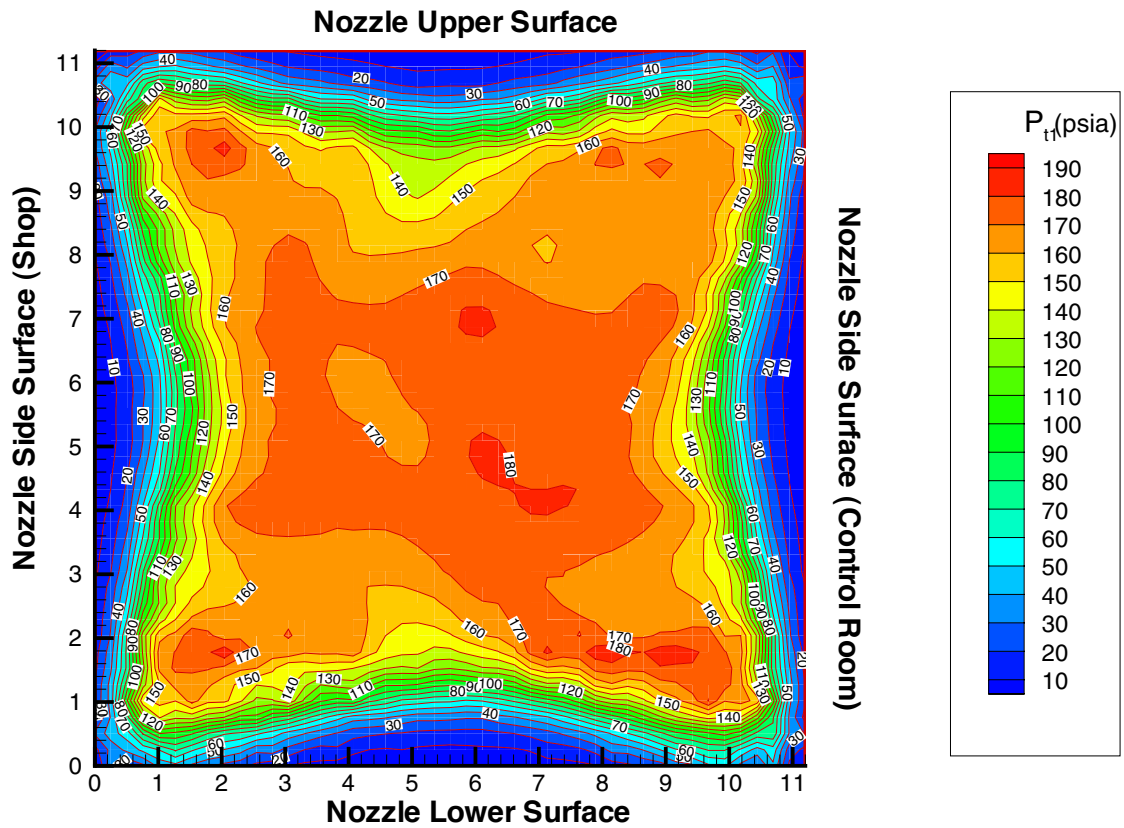


Figure 14t. Freestream total pressure contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

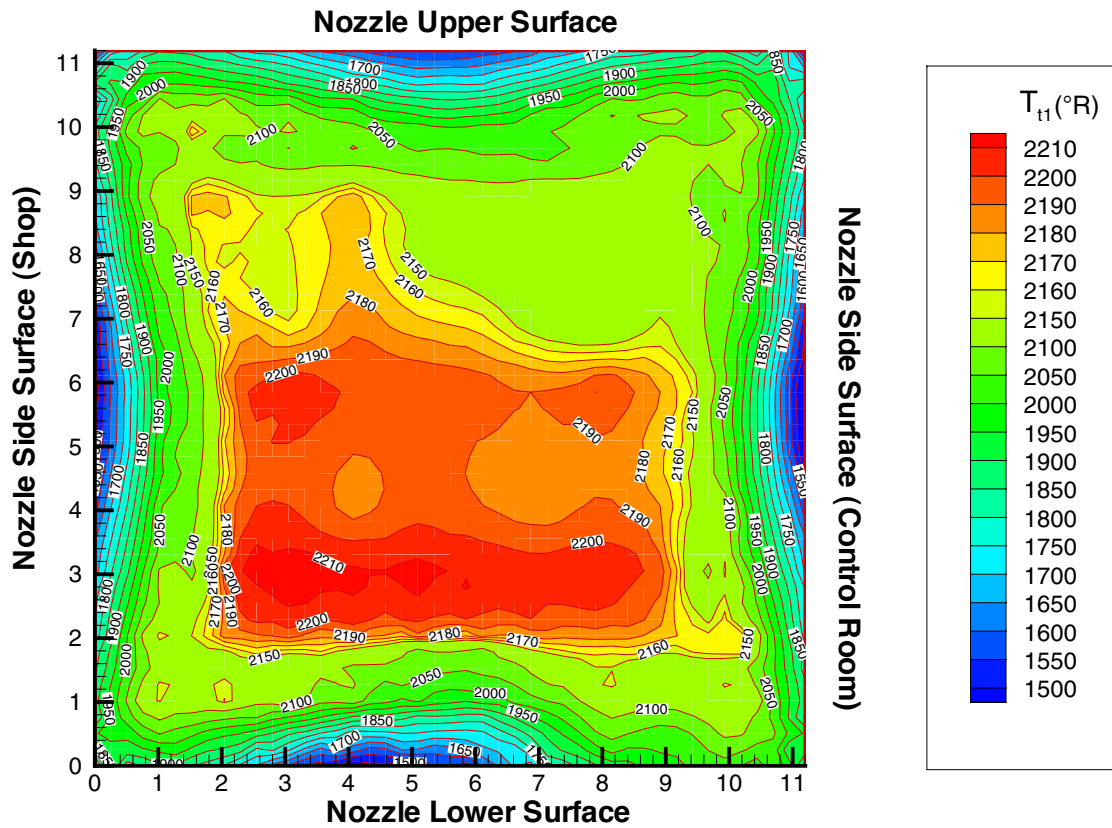


Figure 14u. Freestream total temperature contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

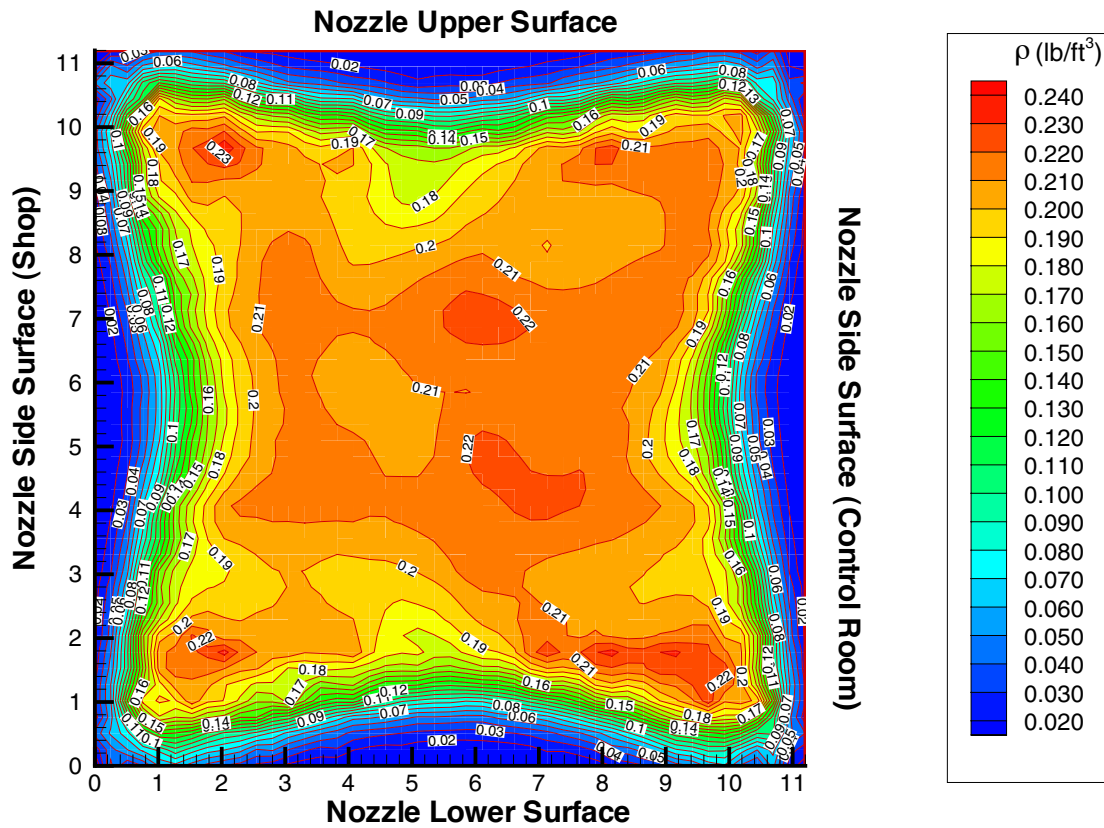


Figure 14v. Freestream total density contours (vibrationally relaxed) at the exit plane of the Mach 4.7 AHSTF nozzle: Mach 5 enthalpy, delta PT1 test point (PT1 = 178 psia, HST = 580 btu/lbm). All dimensions are in inches.

Mach 6 Nozzle, Mach 5 Enthalpy, Test Condition

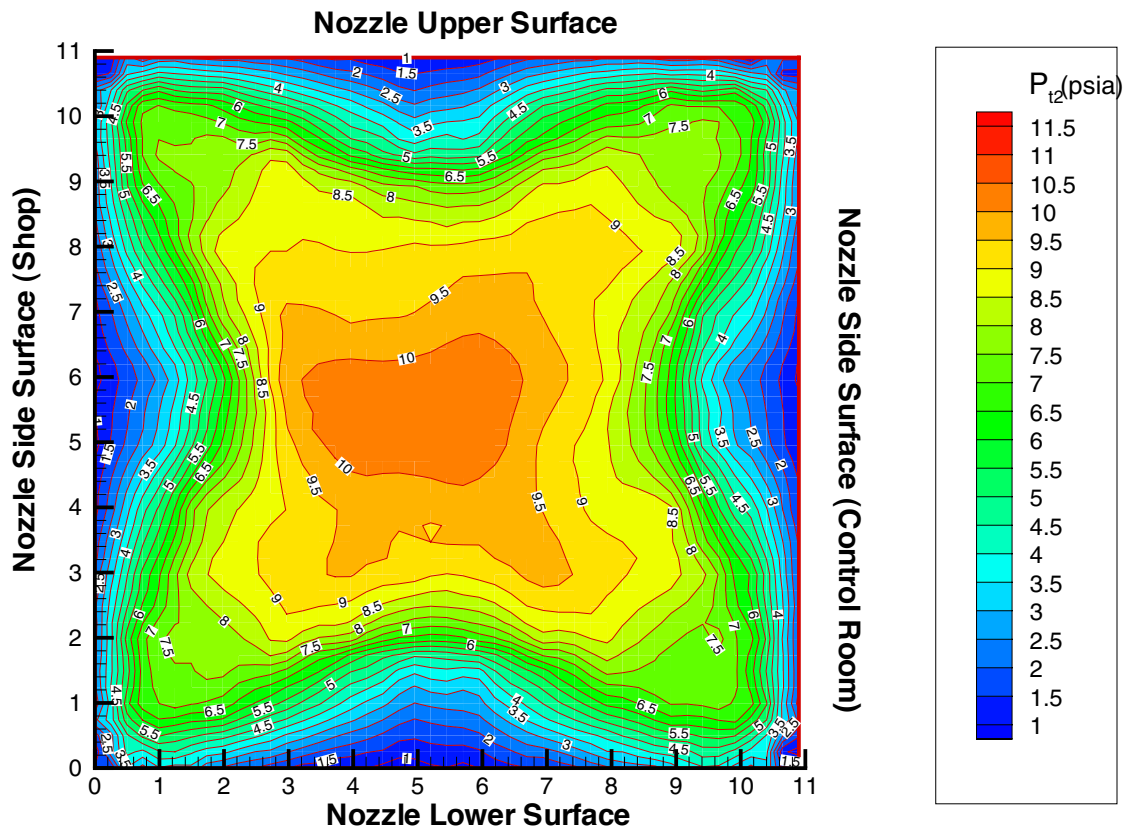


Figure 15a. Pitot pressure contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

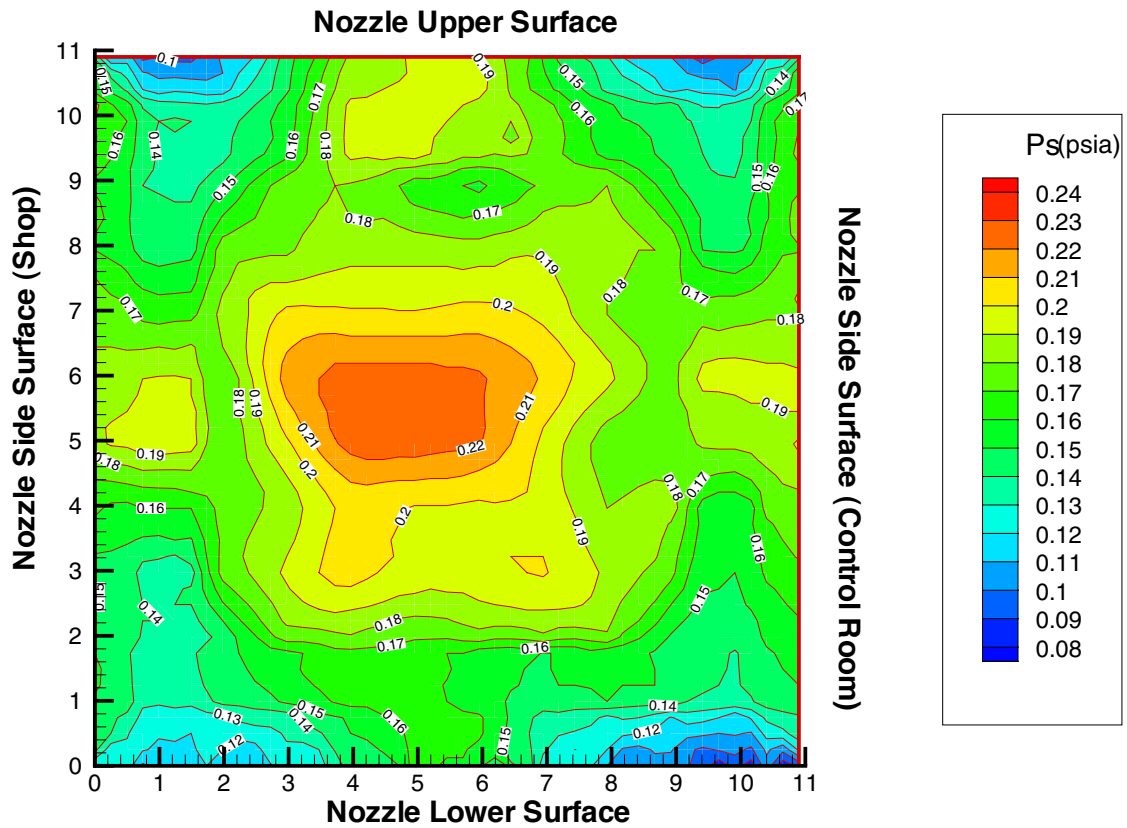


Figure 15b. Static pressure contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point ($PT1 = 400$ psia, $HST = 650$ btu/lbm). All dimensions are in inches.

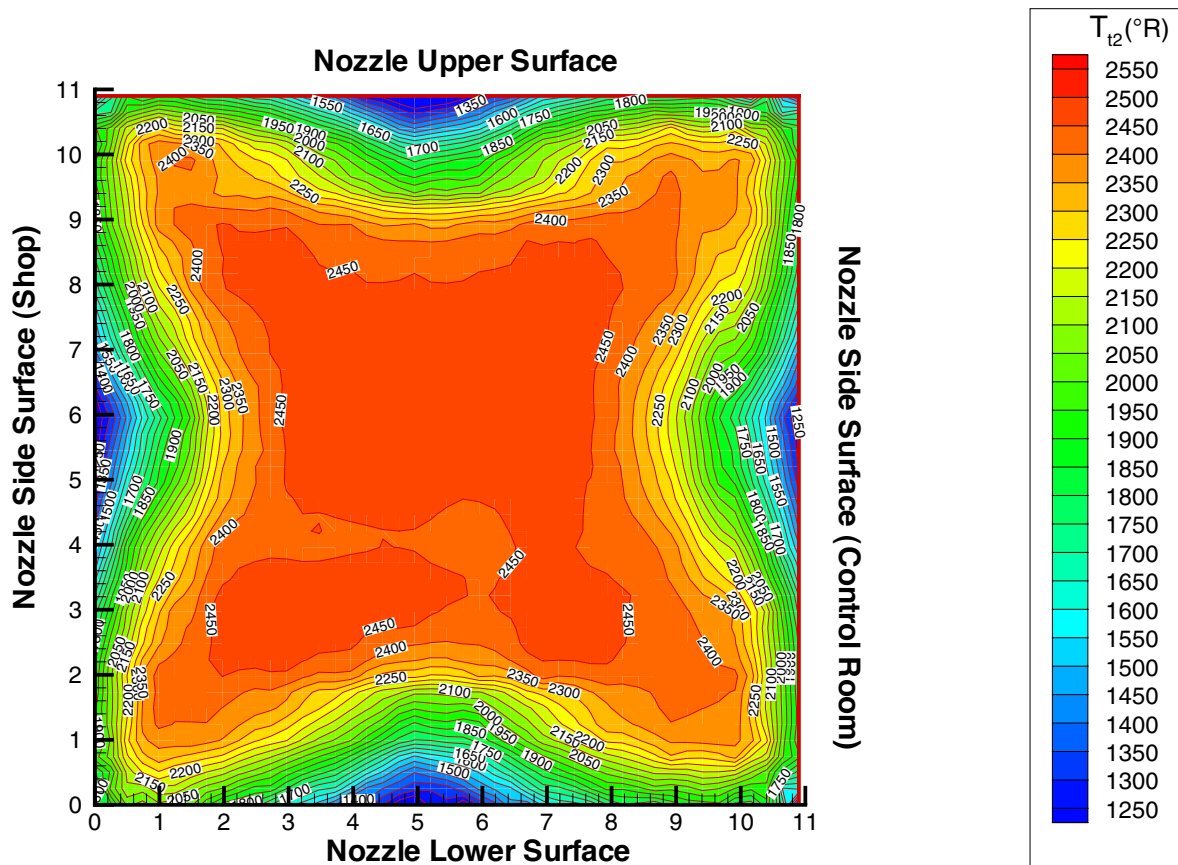


Figure 15c. Total temperature contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

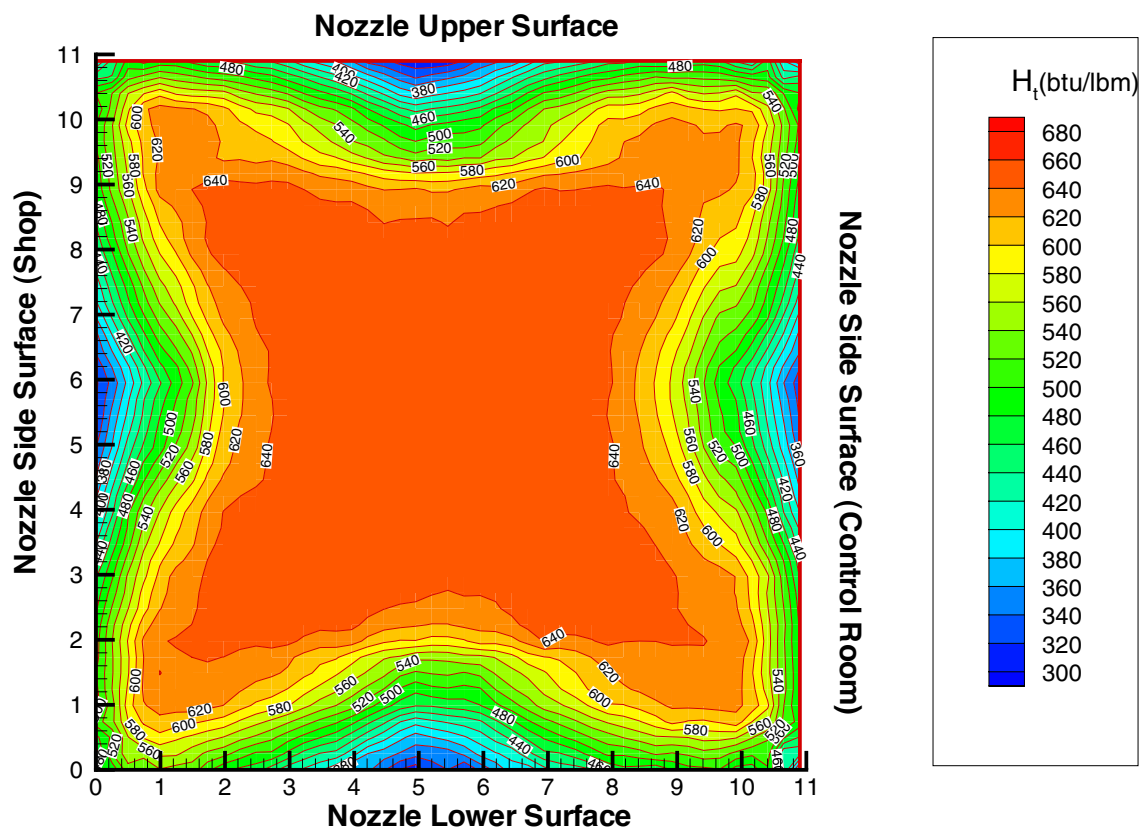


Figure 15d. Total enthalpy contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

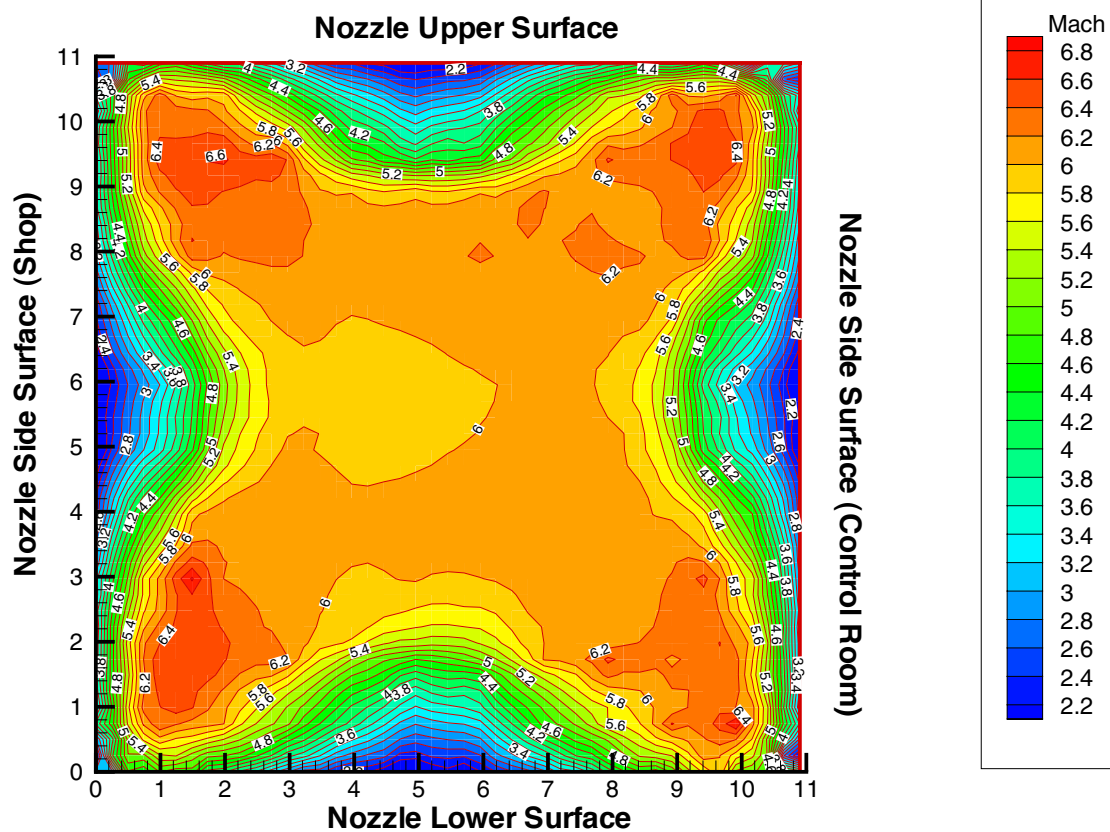


Figure 15e. Mach contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

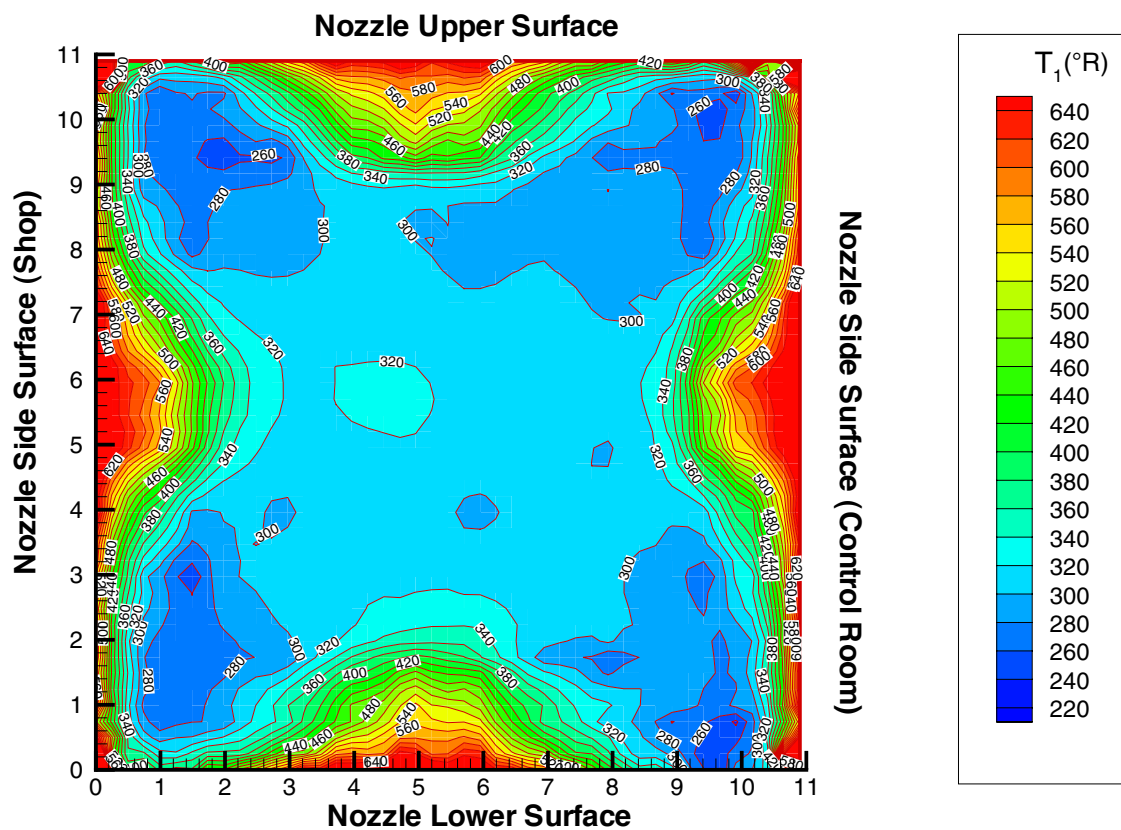


Figure 15f. Static temperature contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

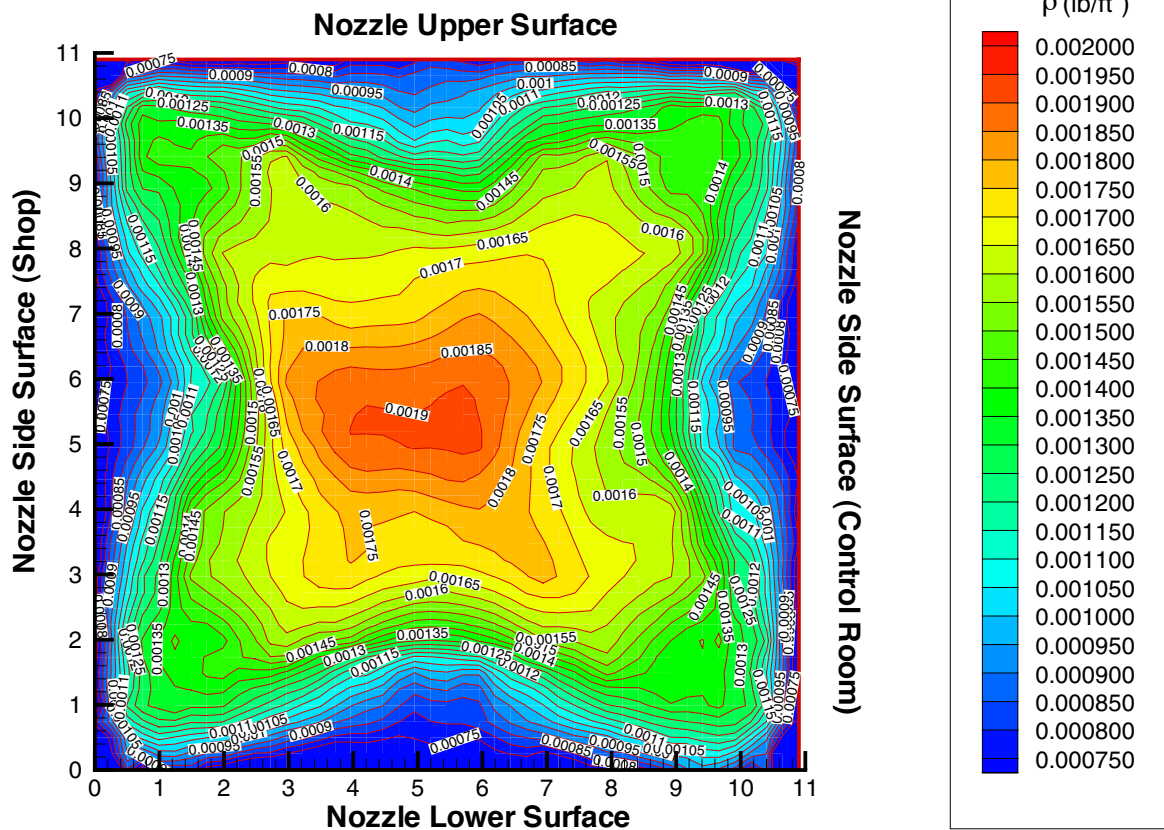


Figure 15g. Static density contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

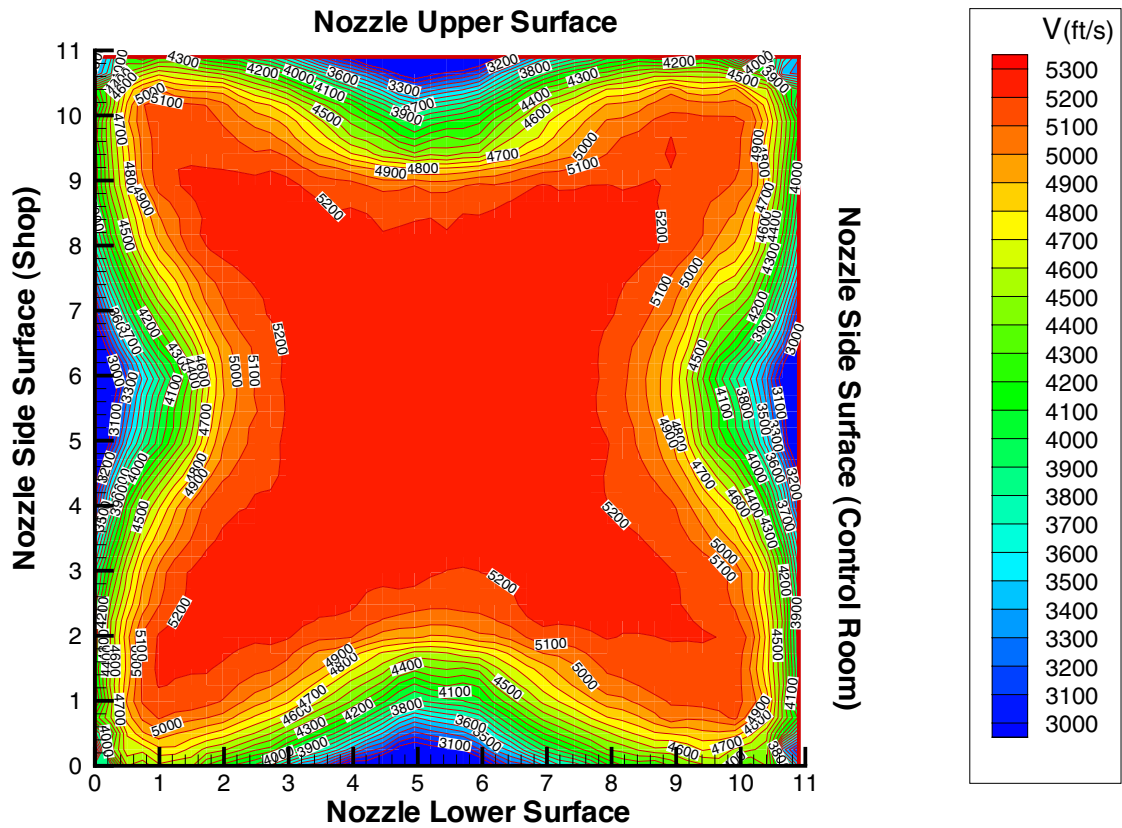


Figure 15h. Velocity contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

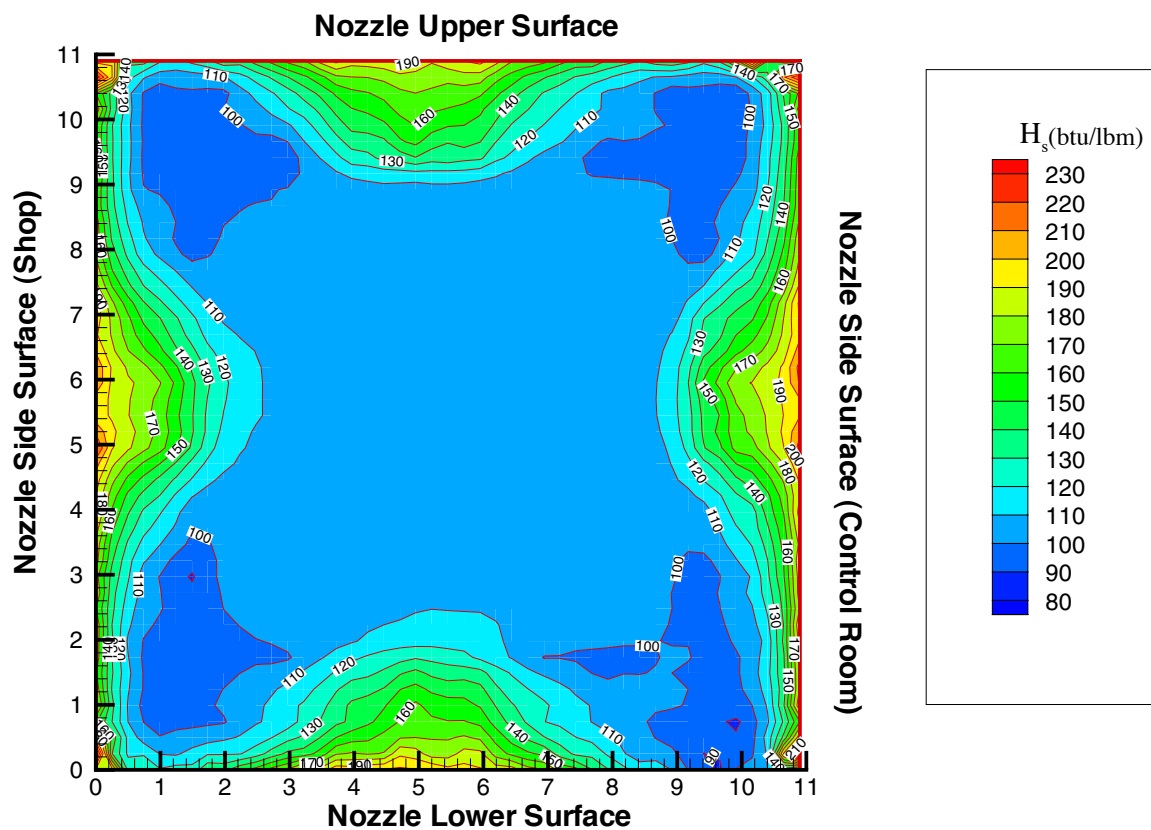


Figure 15i. Static enthalpy contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

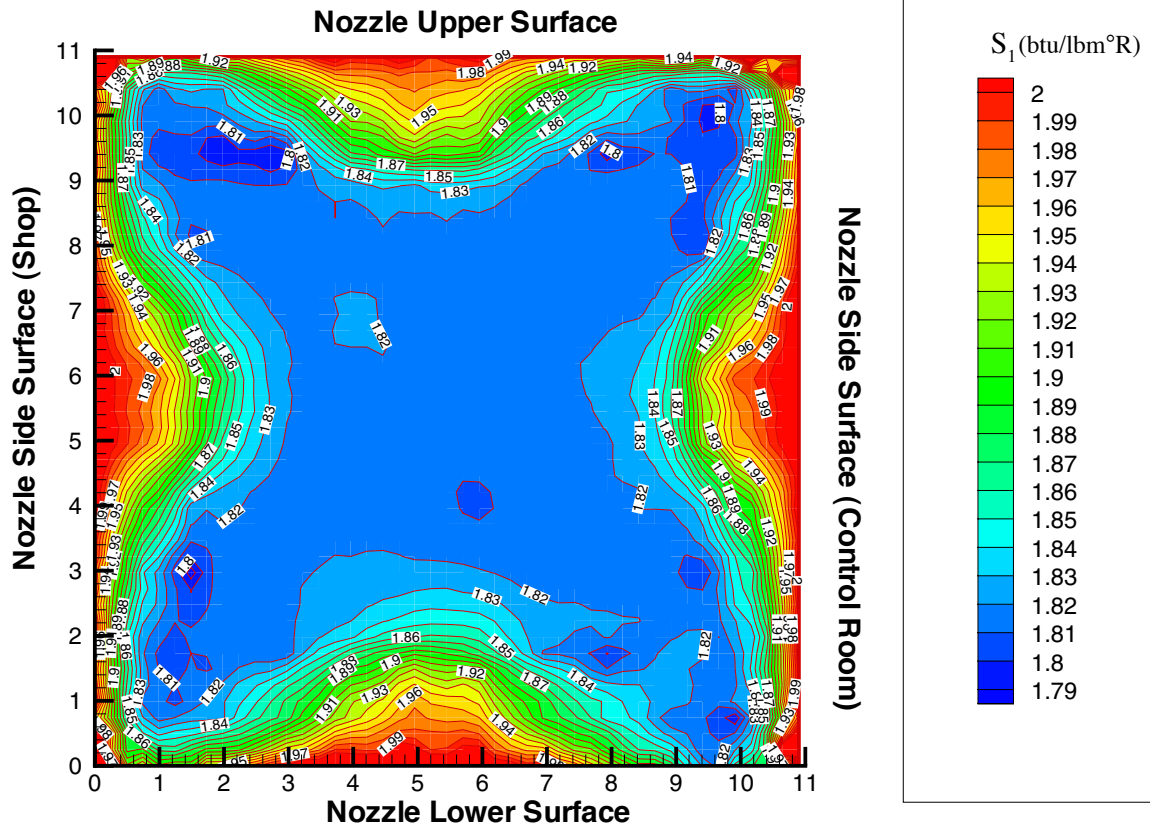


Figure 15j. Entropy contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

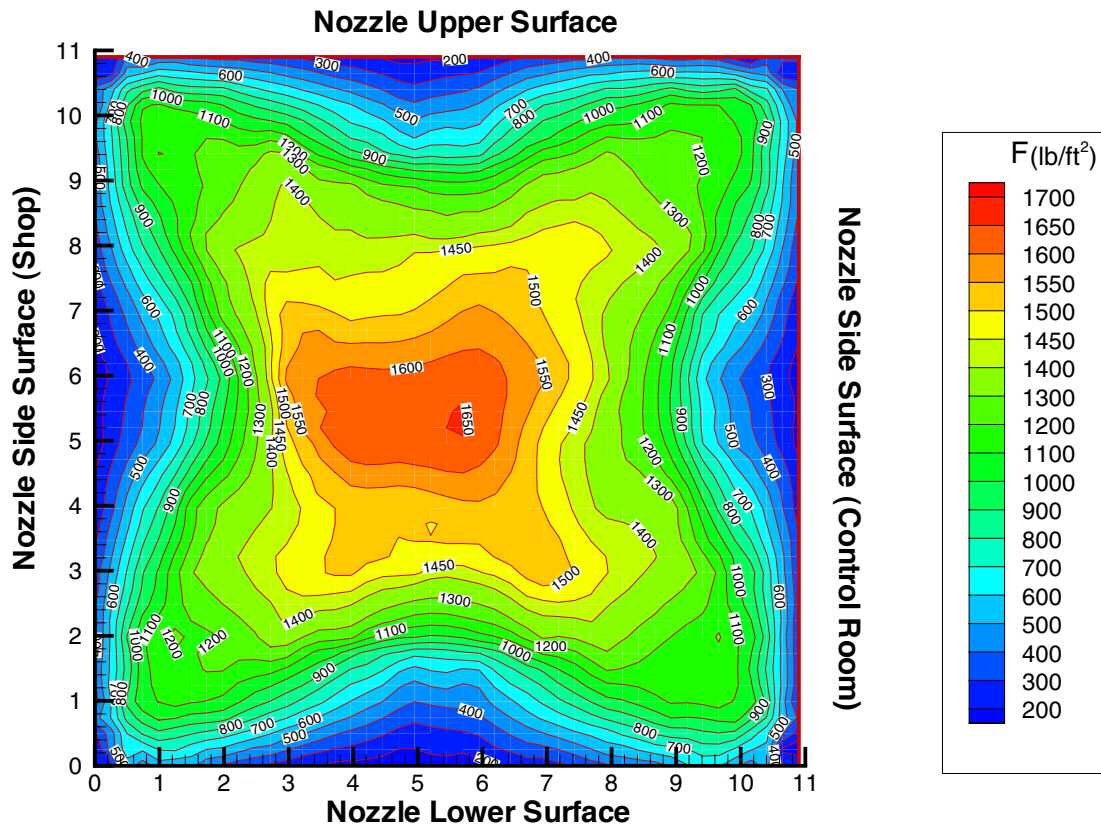


Figure 15k. Stream thrust (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

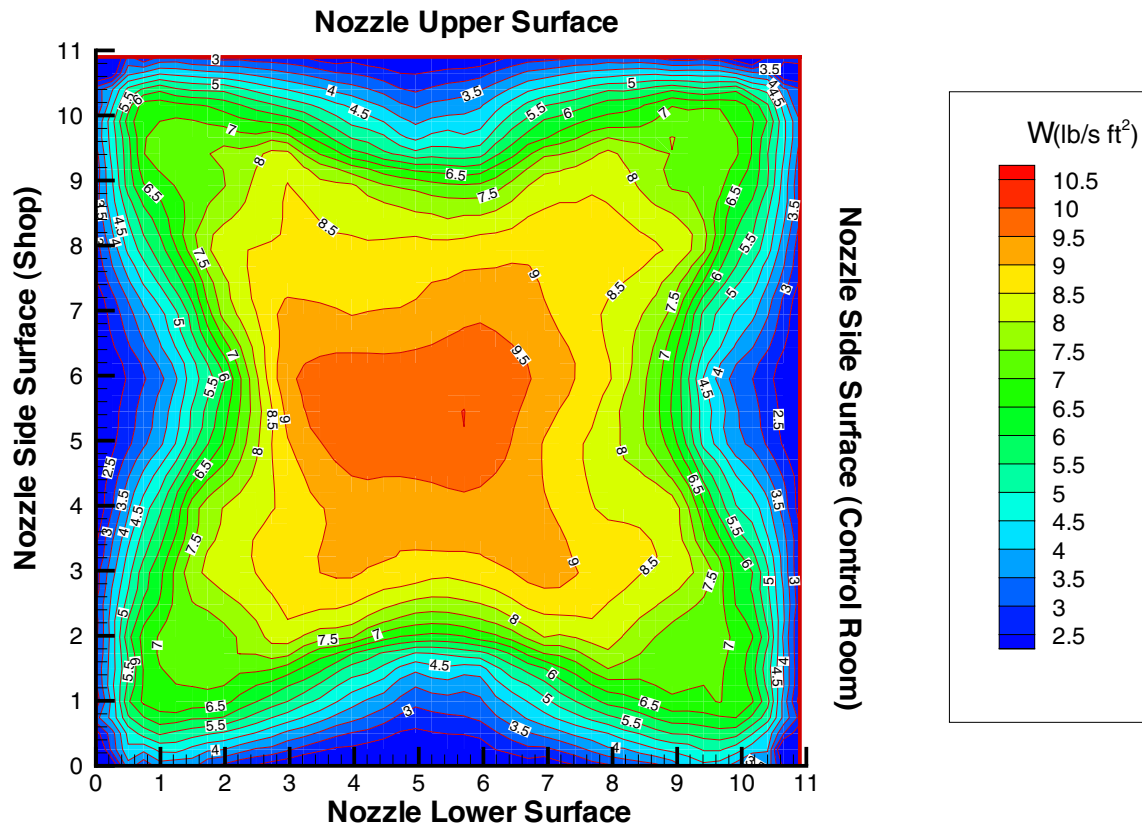


Figure 15l. Mass flux (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

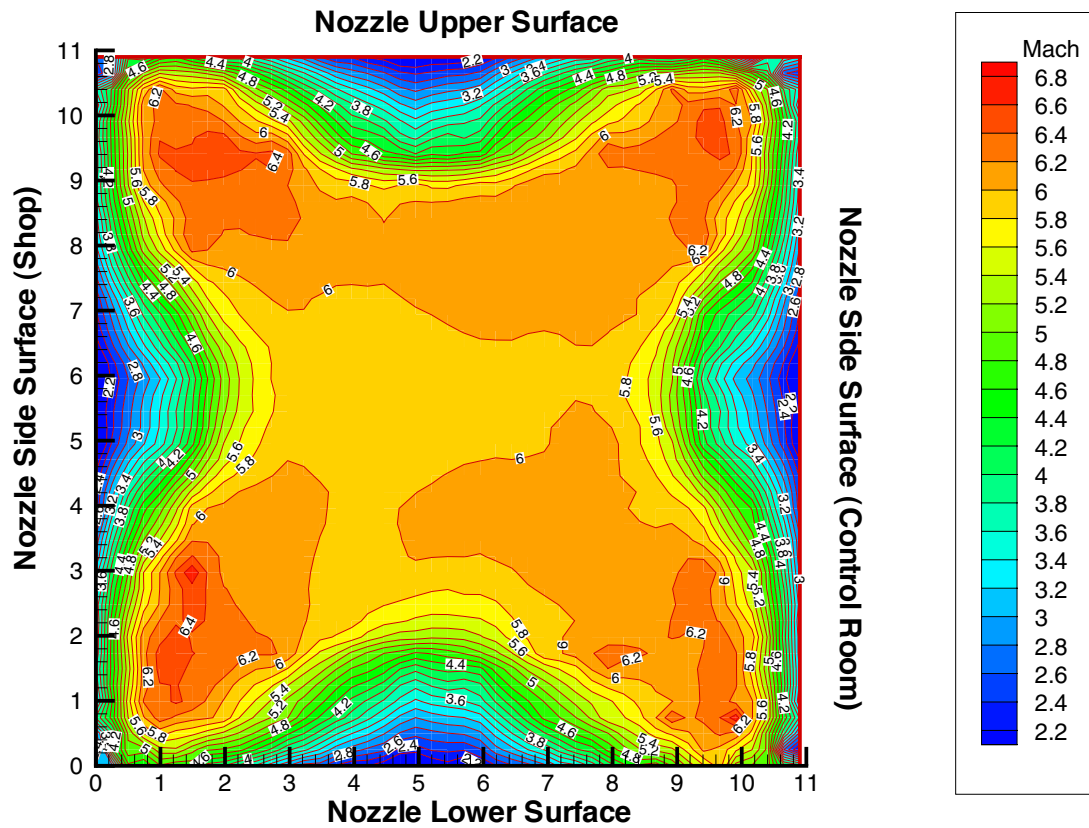


Figure 15m. Mach contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

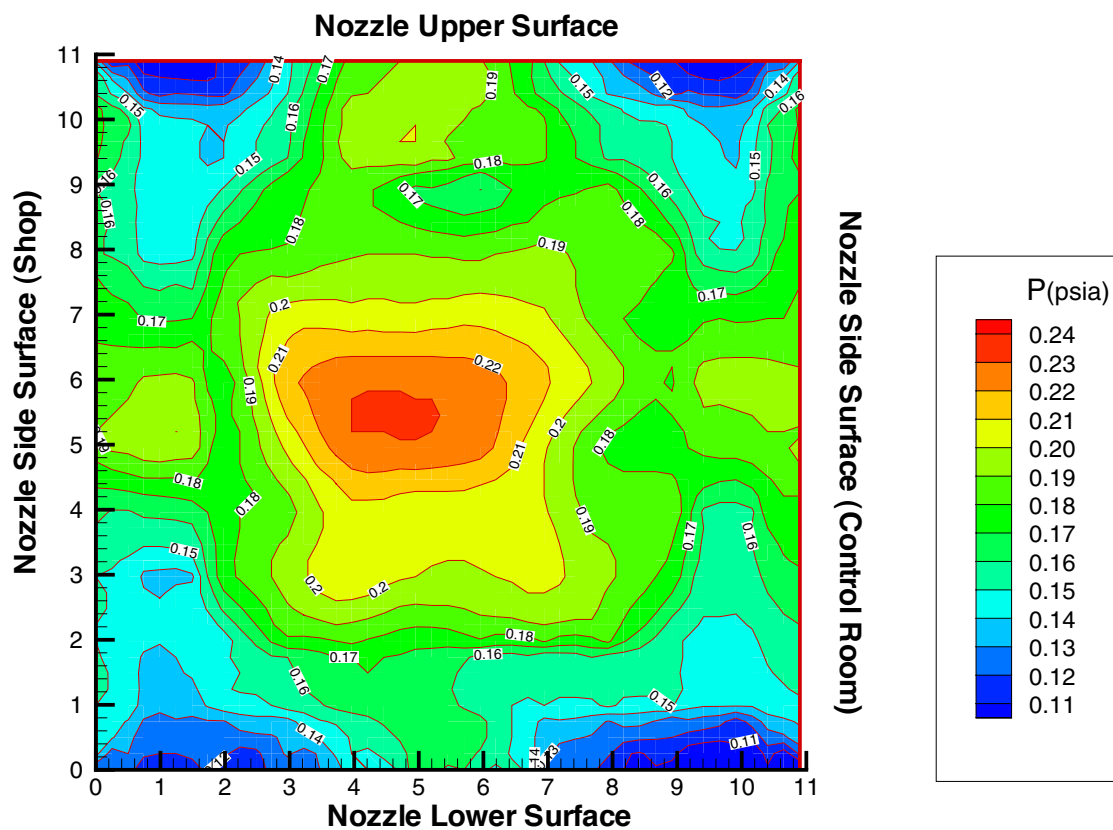


Figure 15n. Static pressure contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

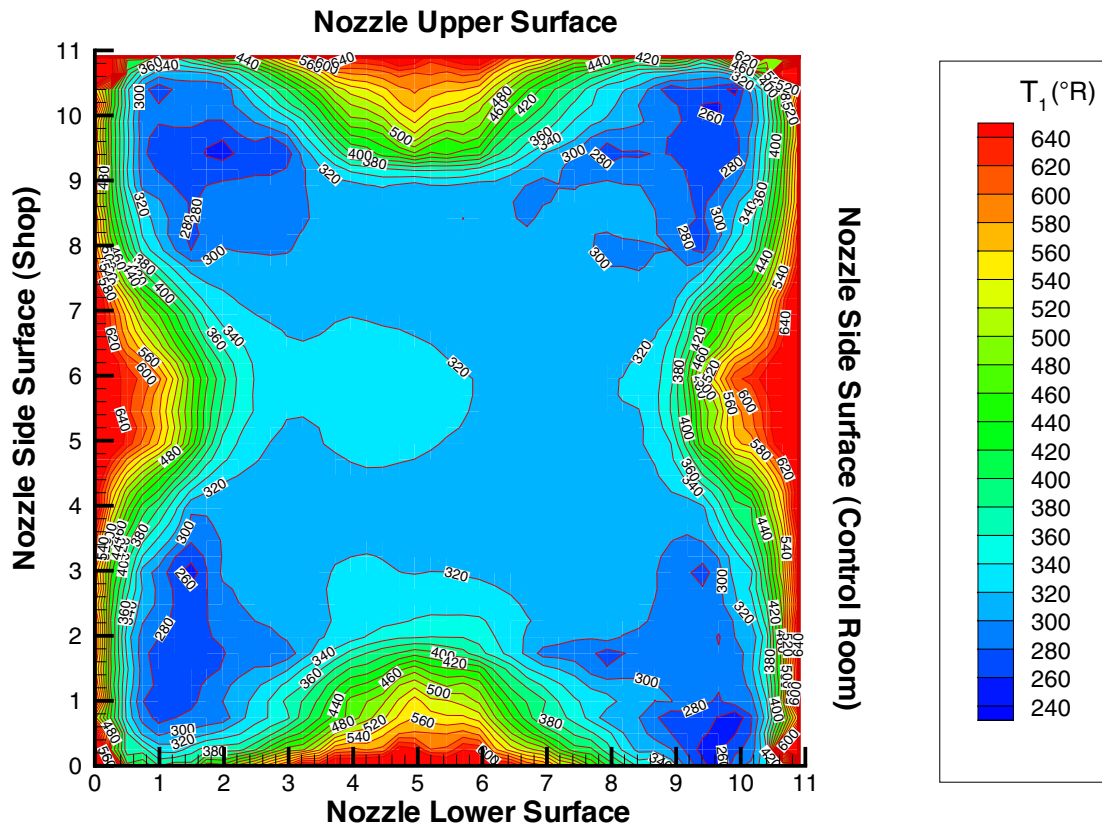


Figure 15o. Static temperature contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

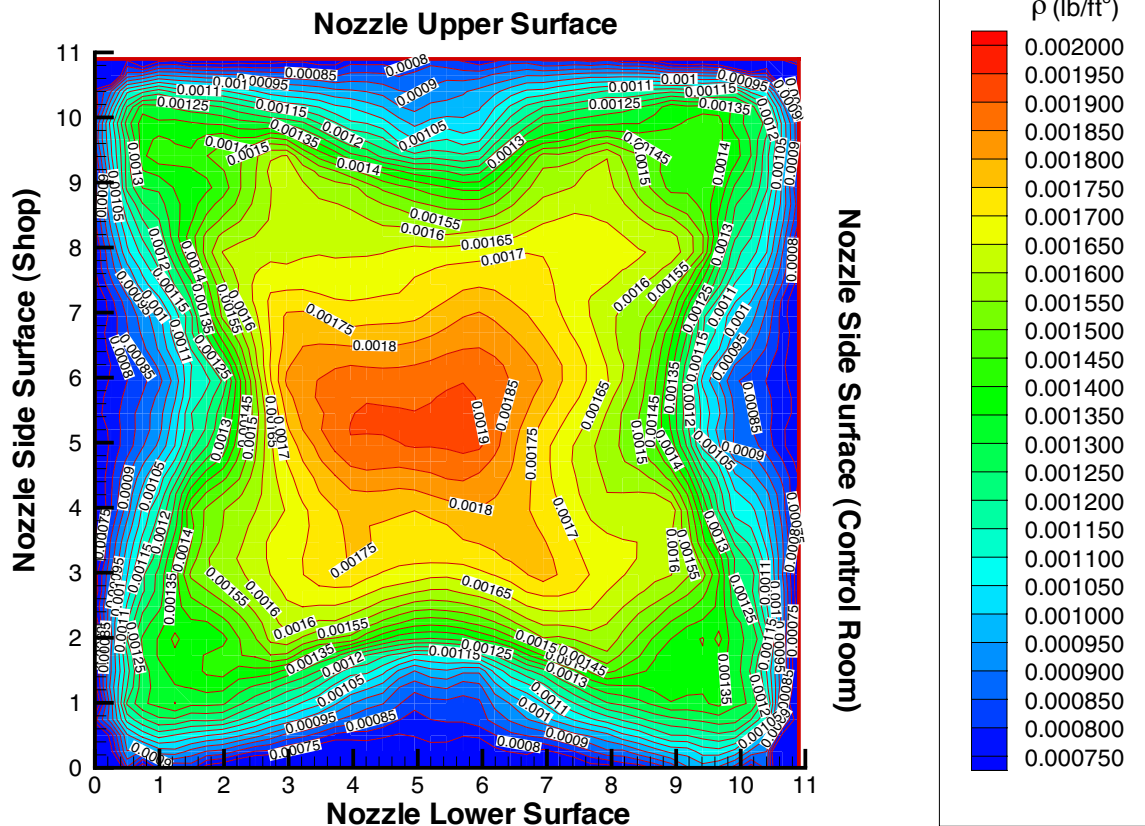


Figure 15p. Static density contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

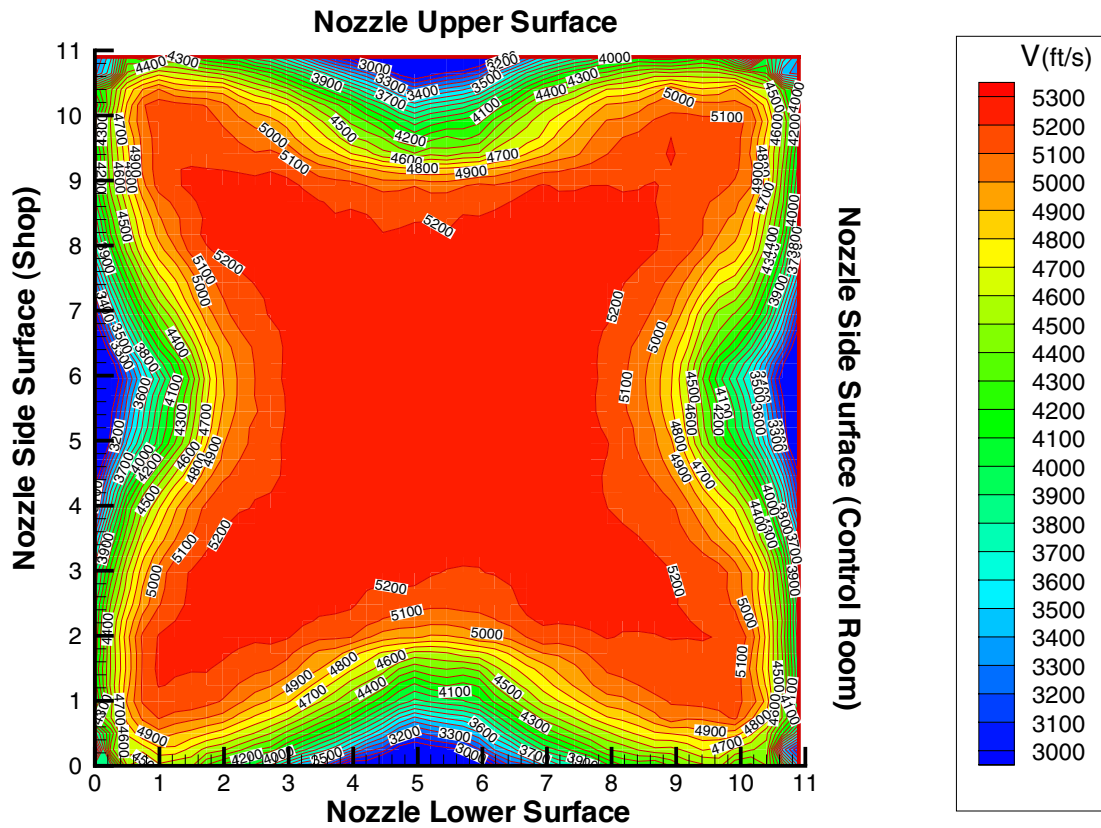


Figure 15q. Velocity contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

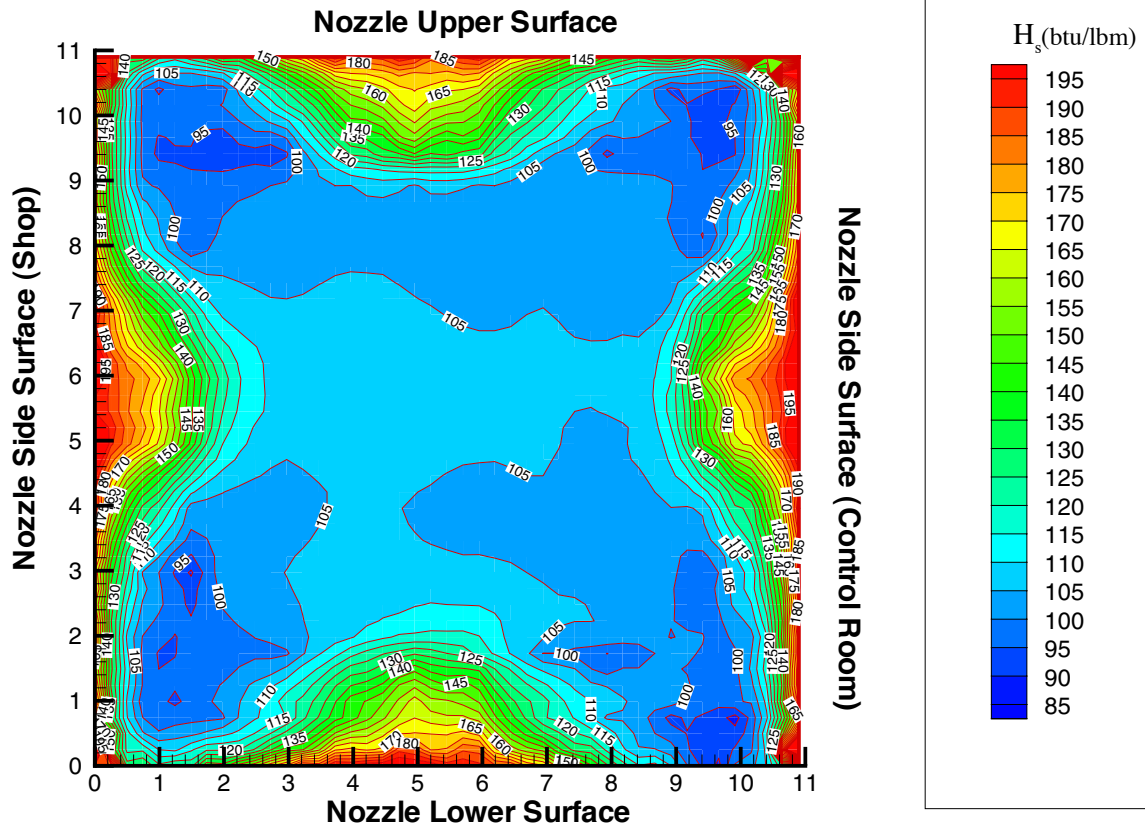


Figure 15r. Static enthalpy contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

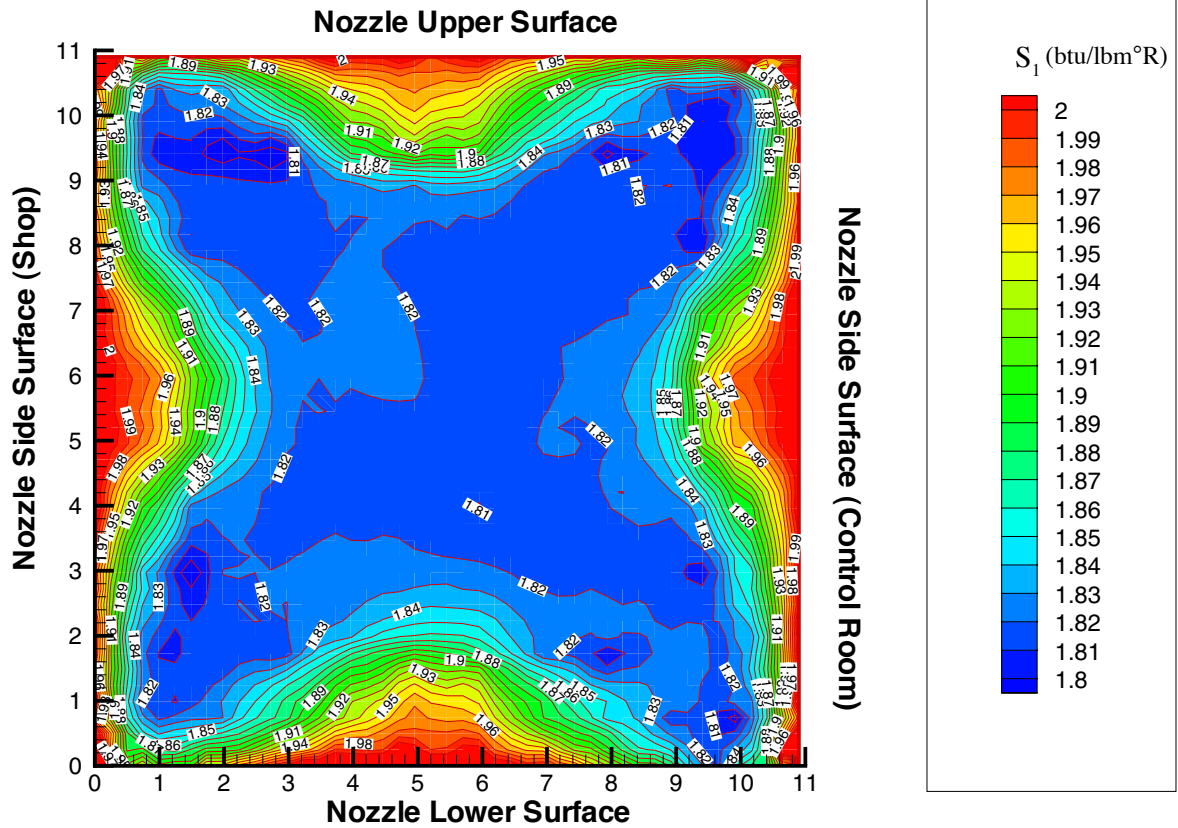


Figure 15s. Entropy contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point ($PT1 = 400$ psia, $HST = 650$ btu/lbm). All dimensions are in inches.

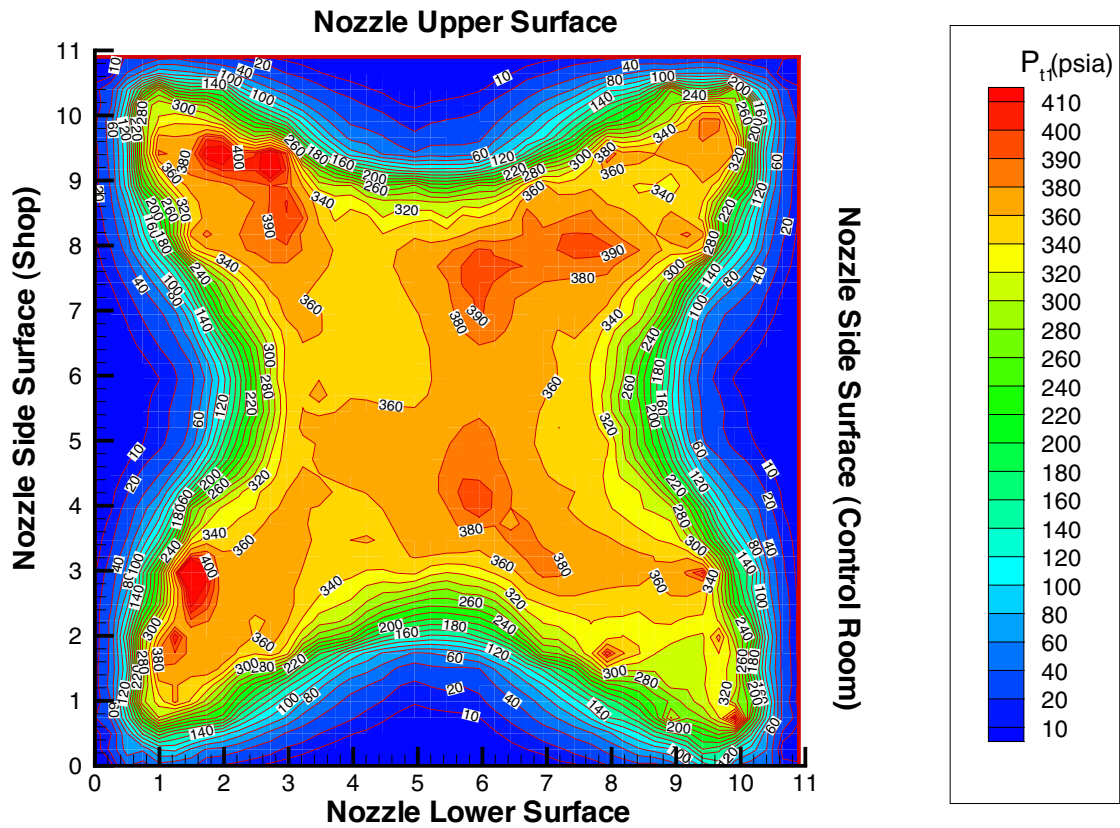


Figure 15t. Freestream total pressure contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

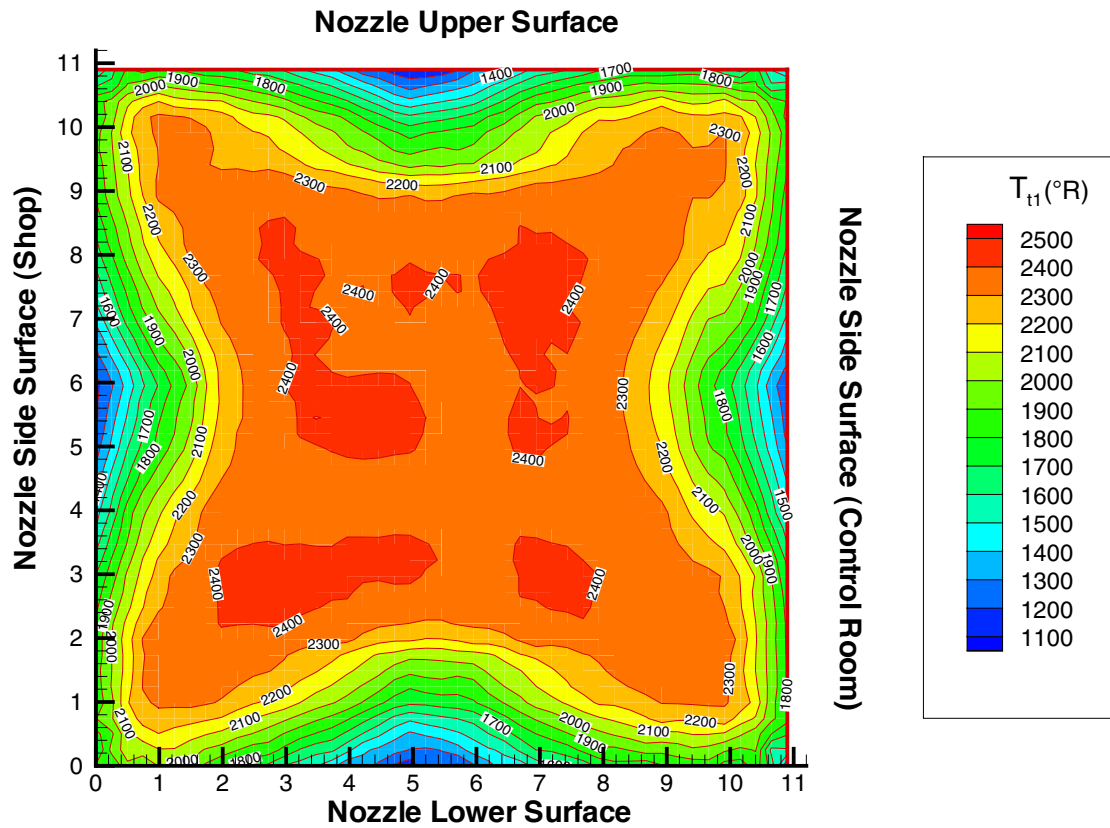


Figure 15u. Freestream total temperature contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

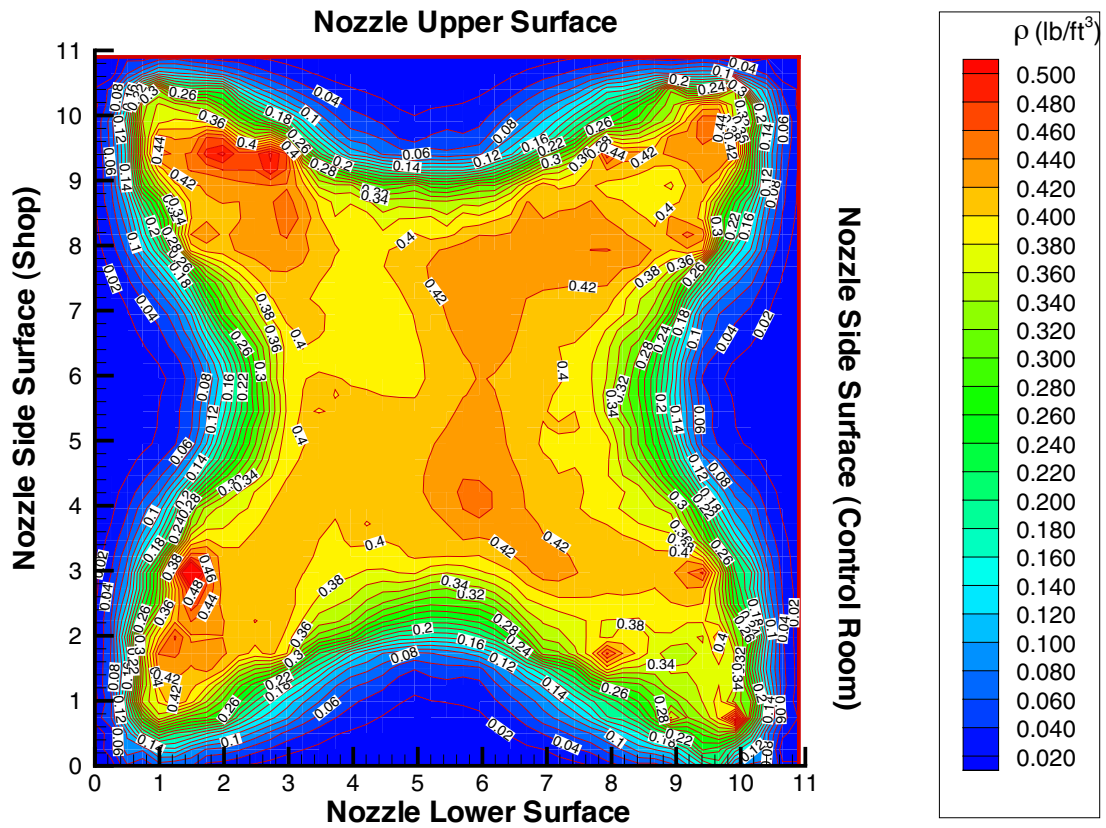


Figure 15v. Freestream total density contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 5 enthalpy test point (PT1 = 400 psia, HST = 650 btu/lbm). All dimensions are in inches.

Mach 6 Nozzle, Mach 6 Enthalpy, Test Condition

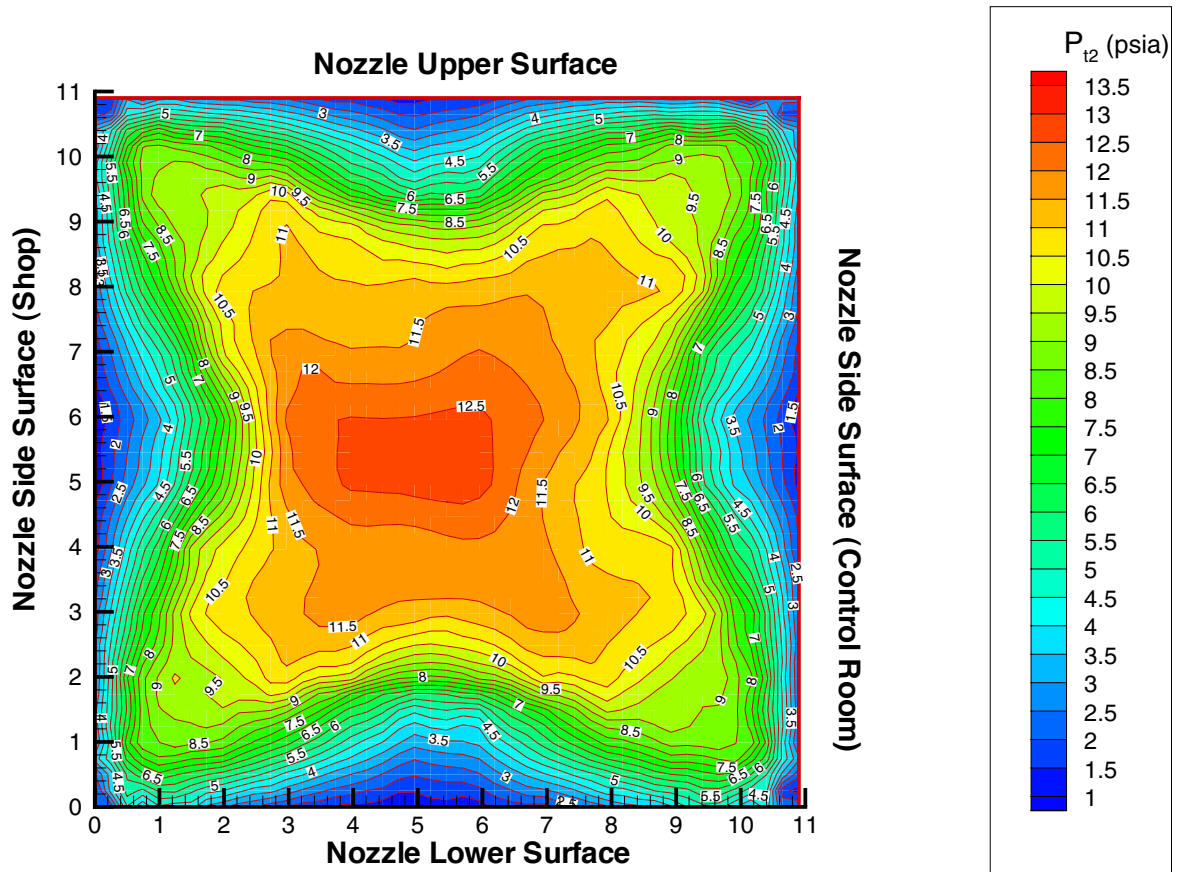


Figure 16a. Pitot pressure contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

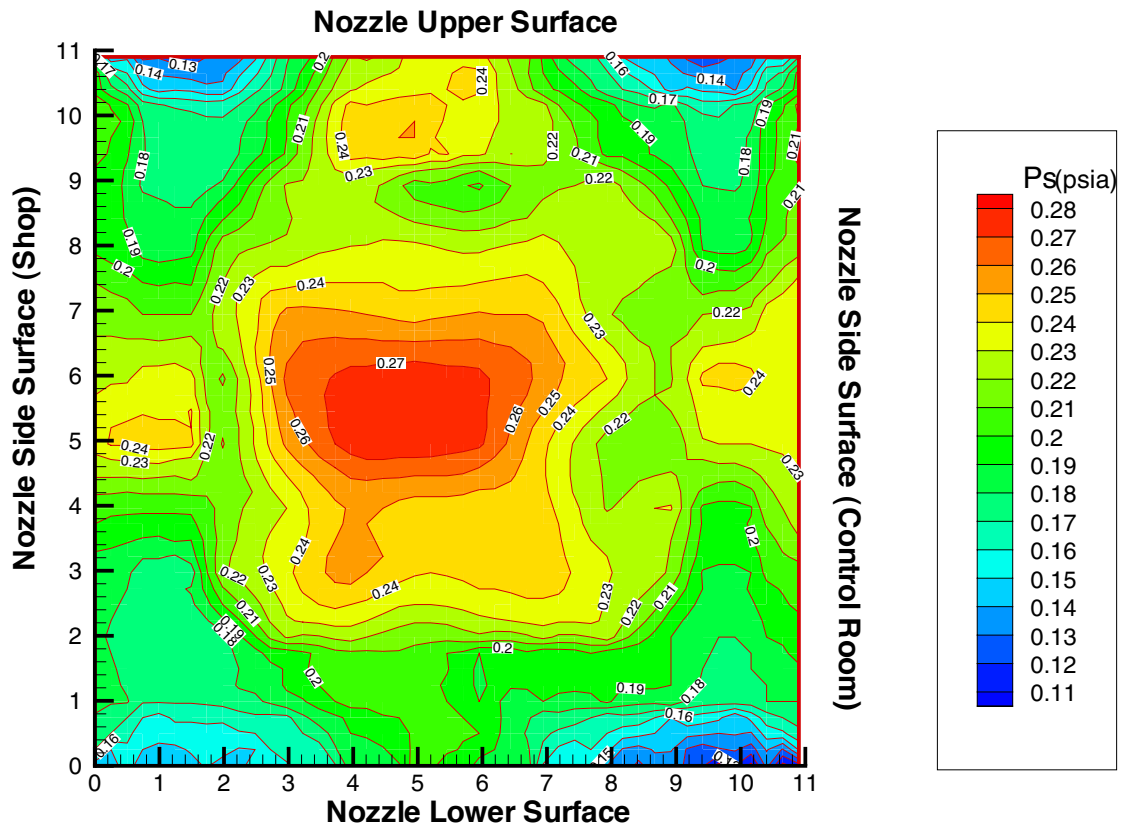


Figure 16b. Static pressure contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point ($PT1 = 495$ psia, $HST = 795$ btu/lbm). All dimensions are in inches.

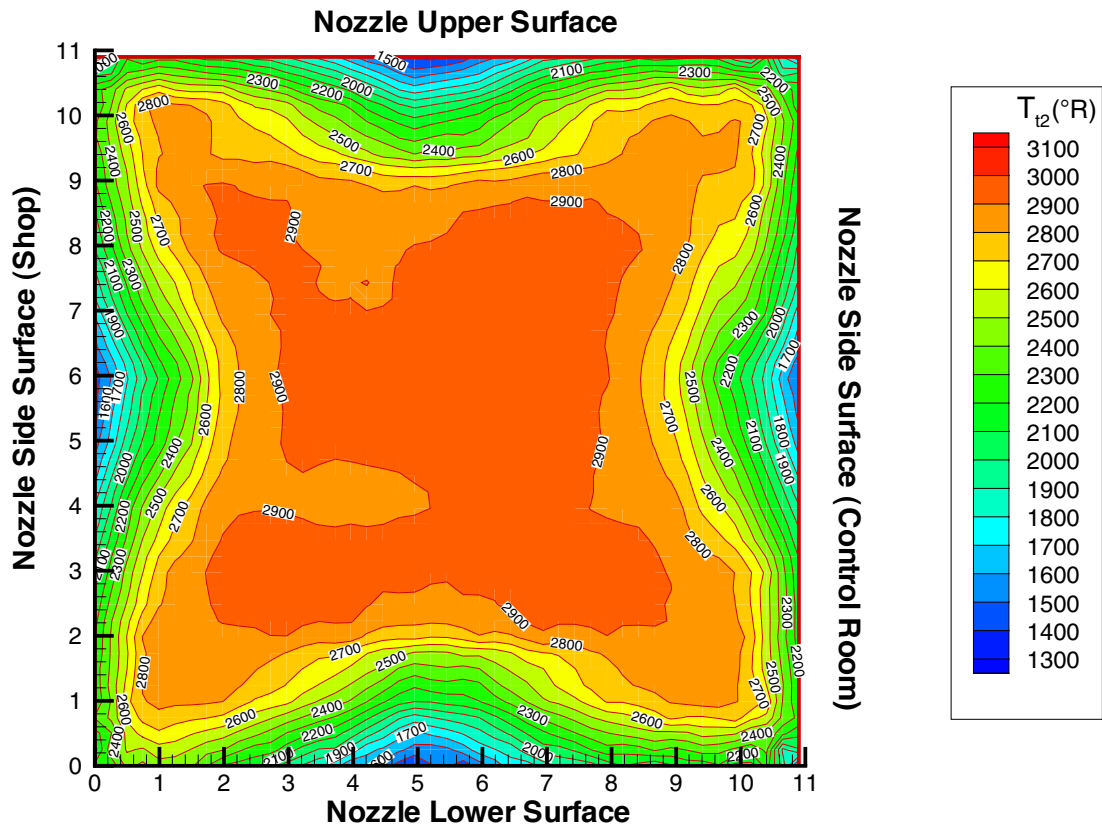


Figure 16c. Total temperature contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

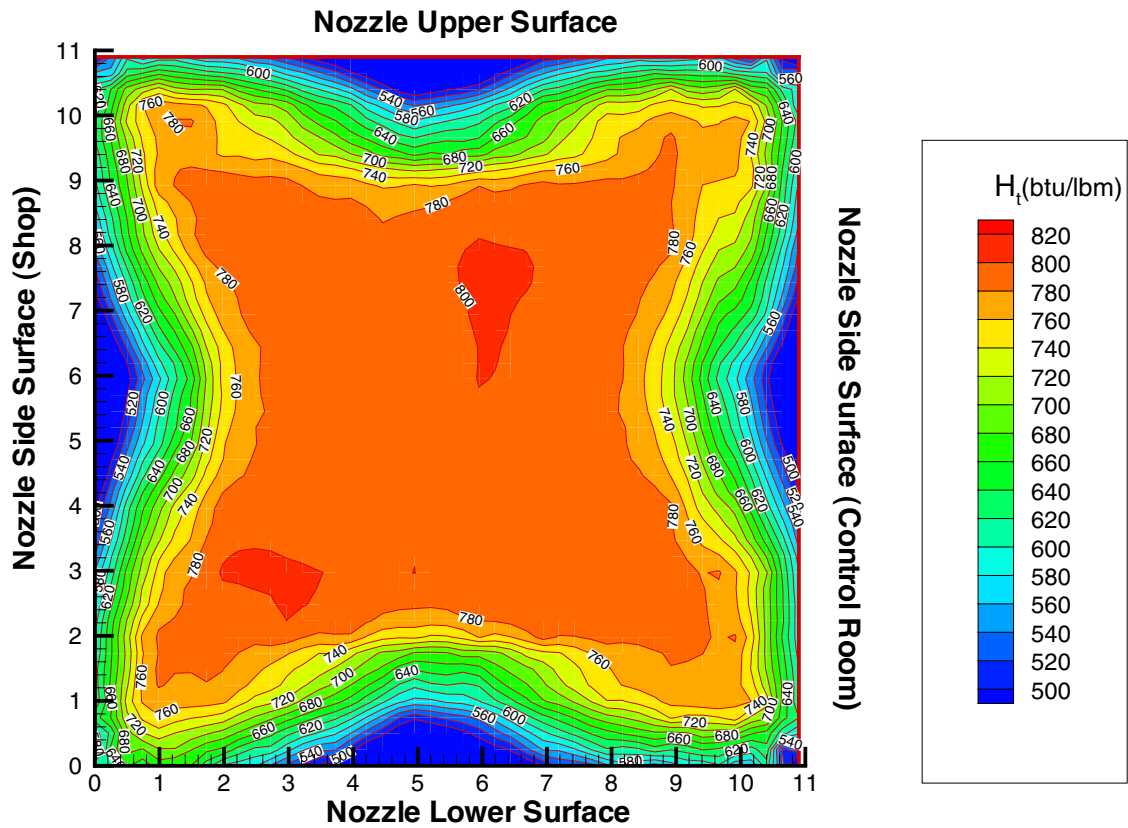


Figure 16d. Total enthalpy contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

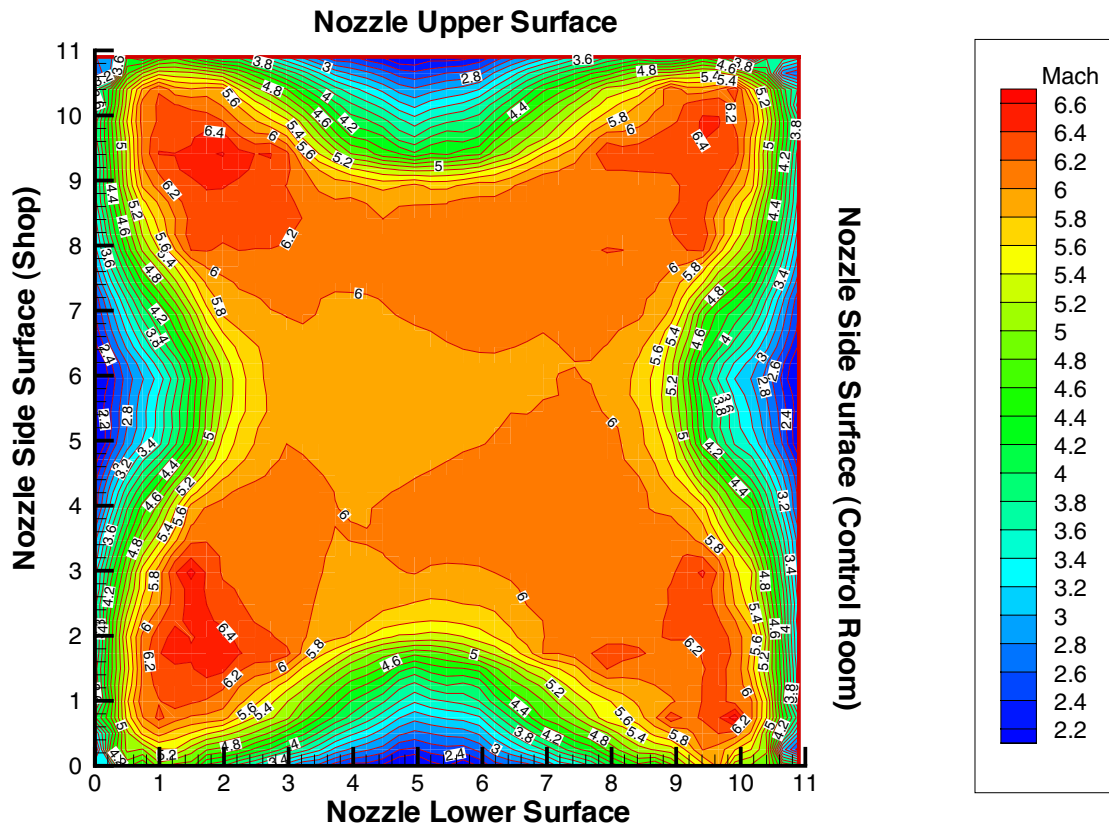


Figure 16e. Mach contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

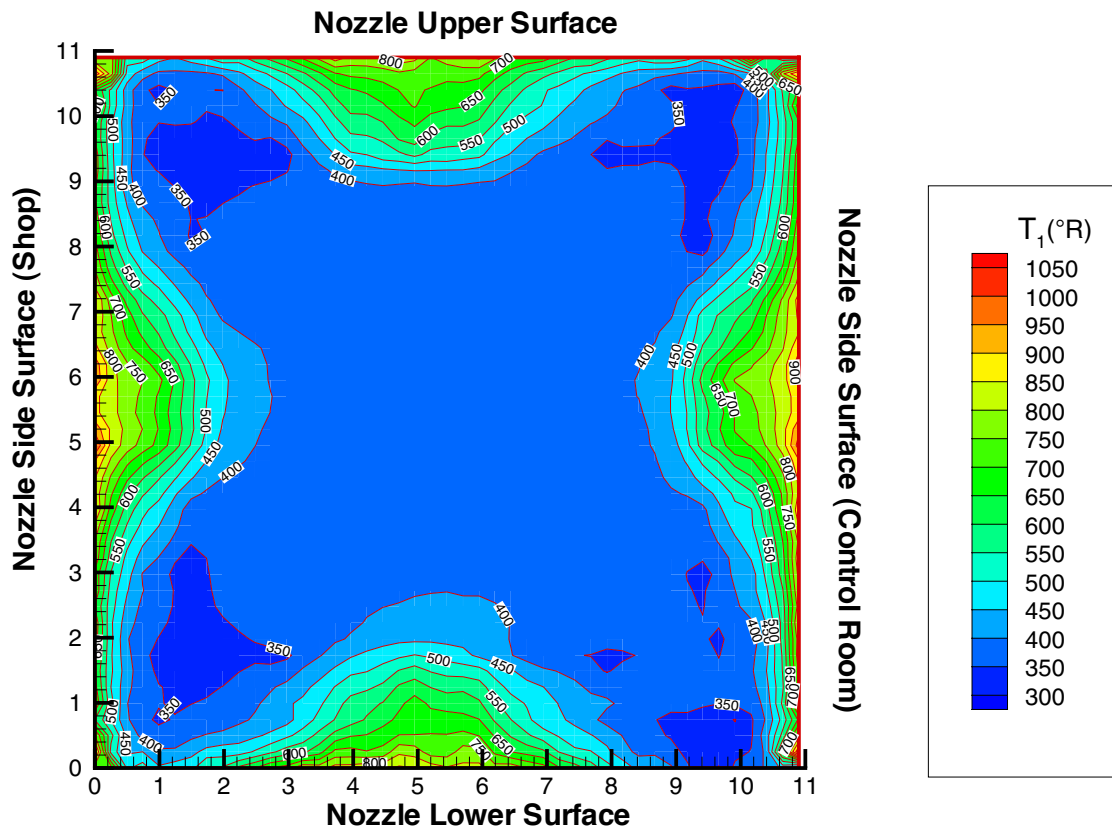


Figure 16f. Static temperature contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

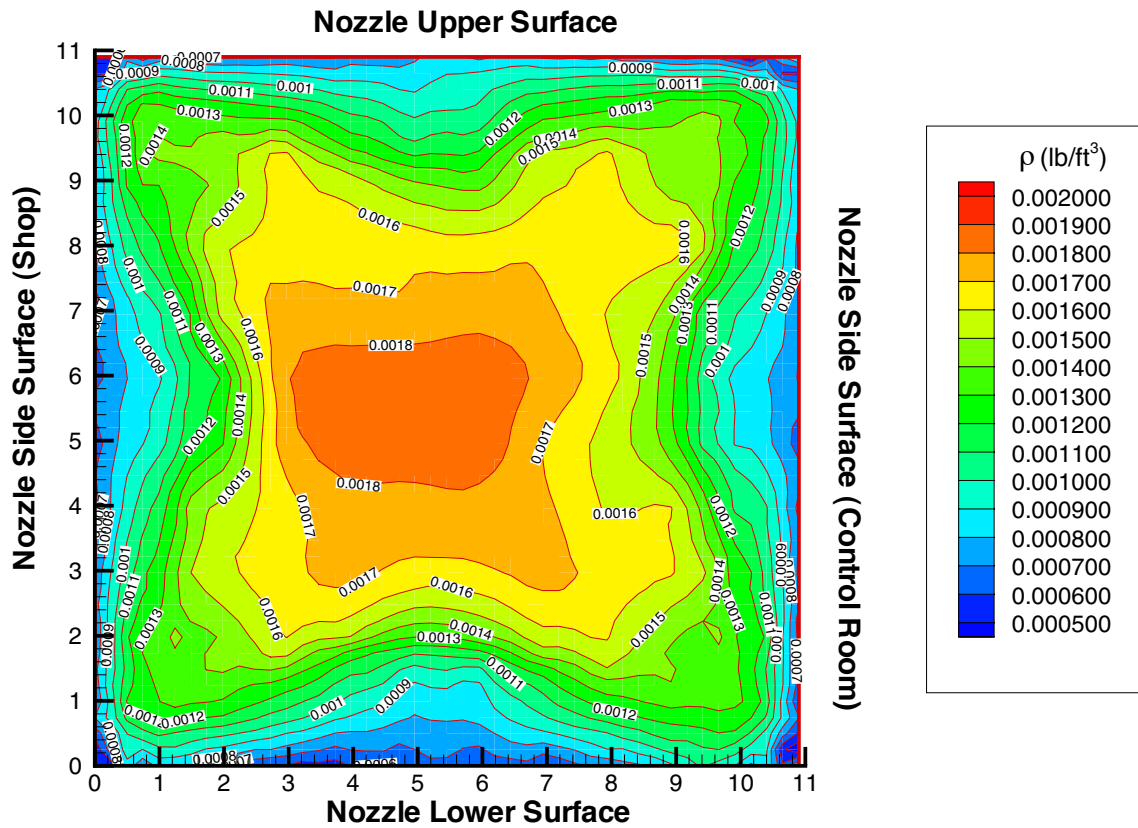


Figure 16g. Static density contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

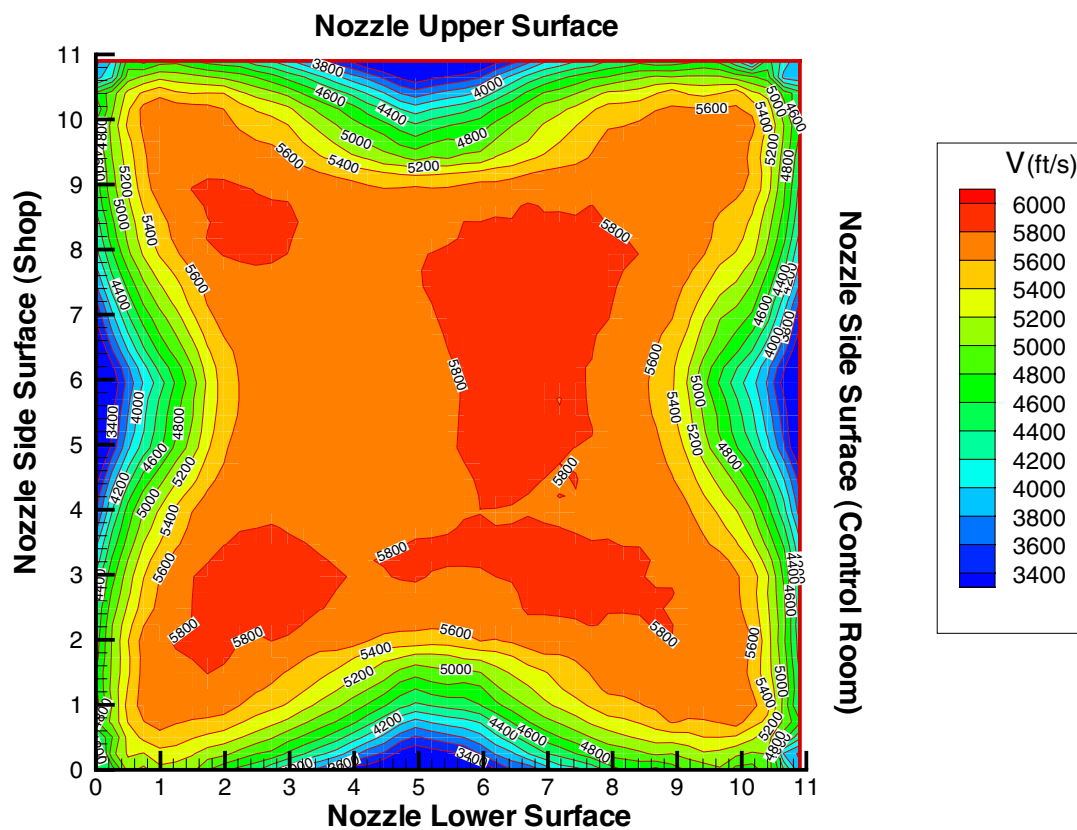


Figure 16h. Velocity contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

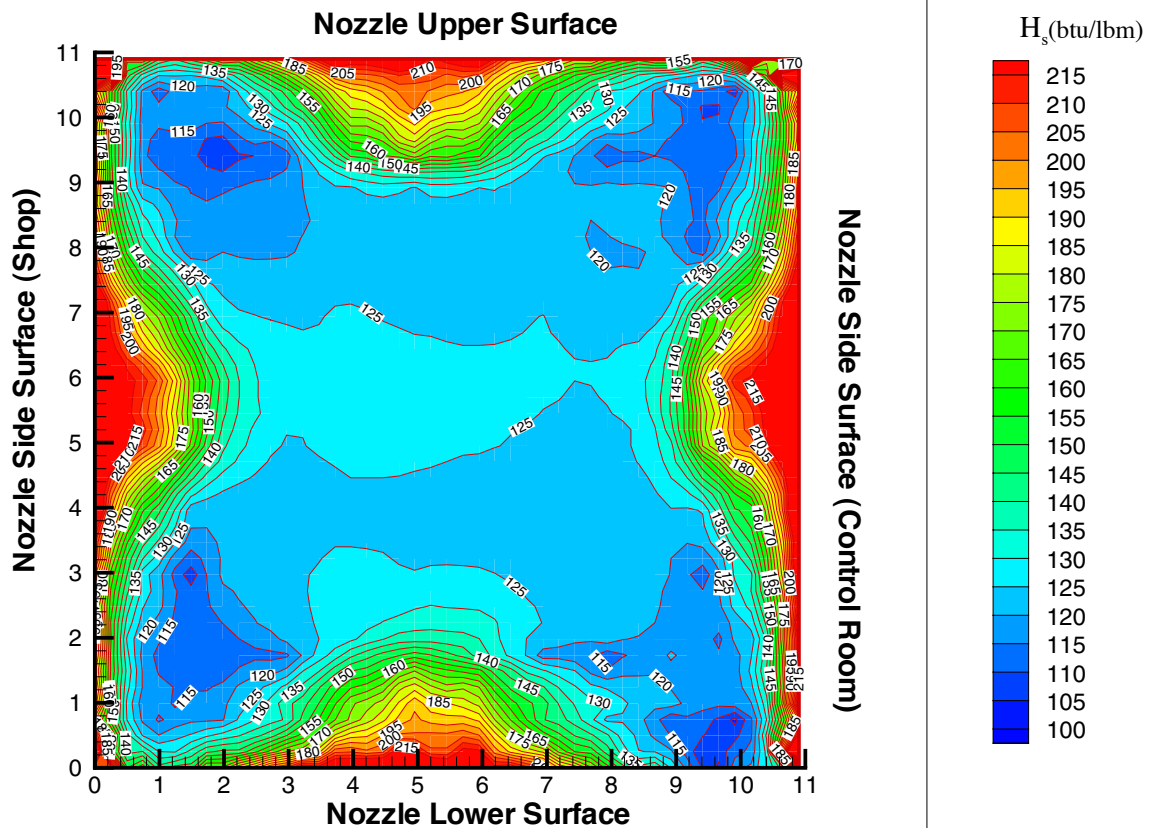


Figure 16i. Static enthalpy contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

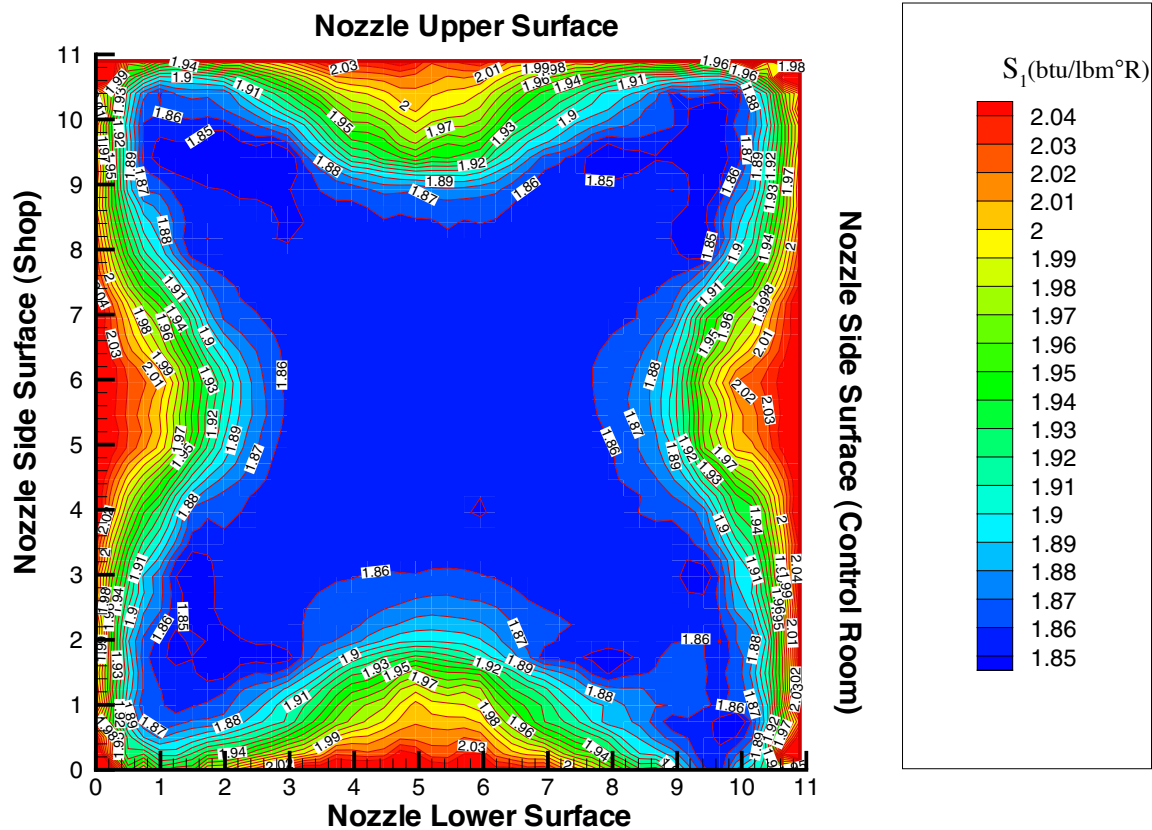


Figure 16j. Entropy contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

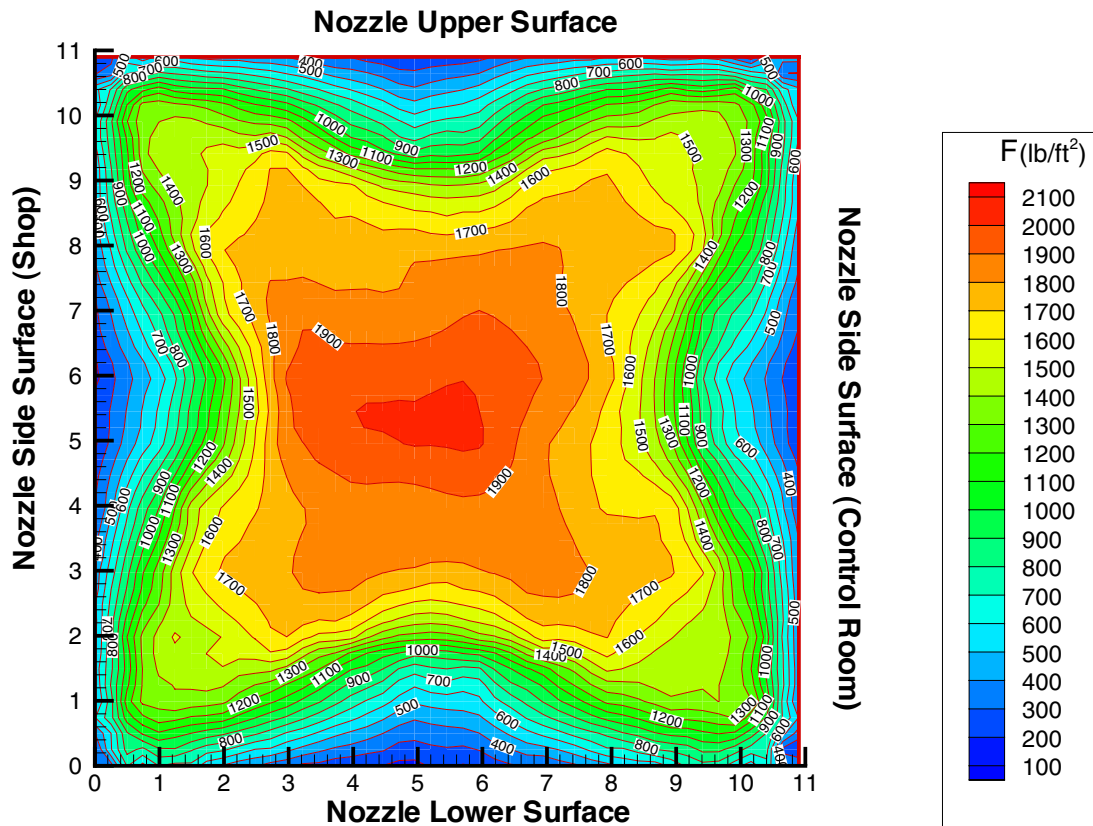


Figure 16k. Stream thrust contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

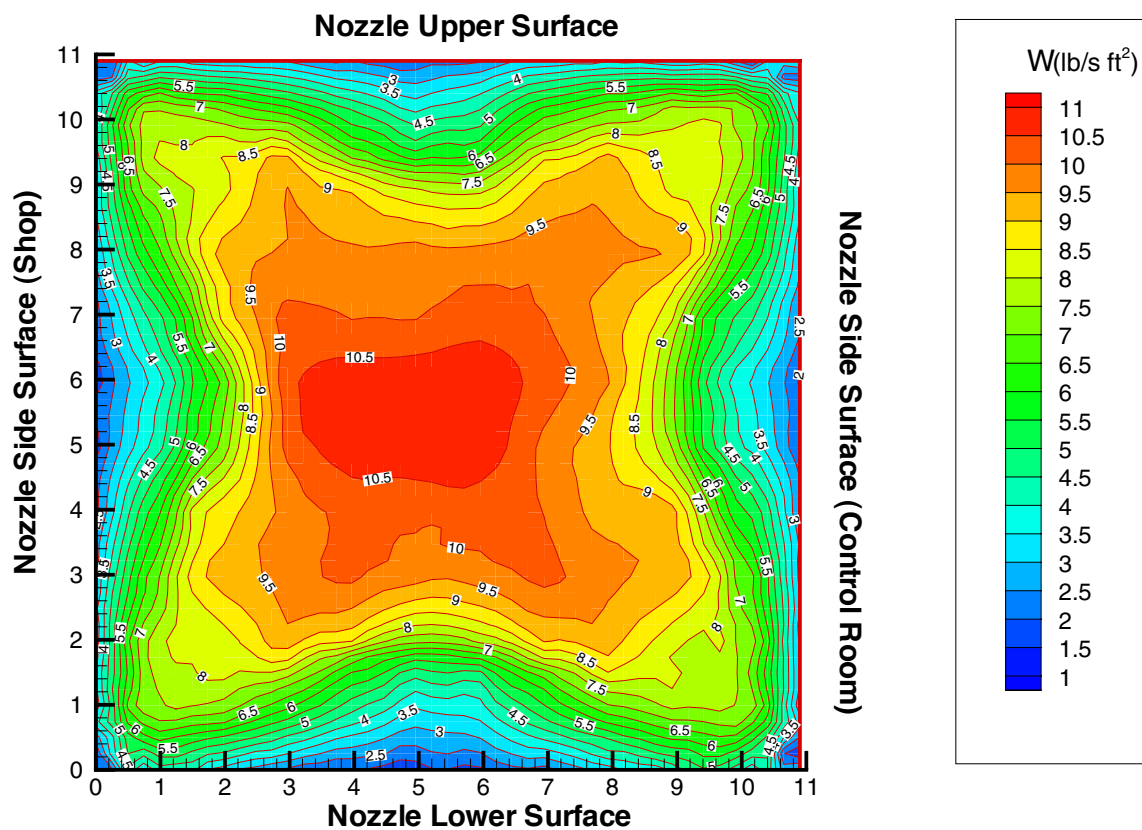


Figure 16l. Mass flux contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

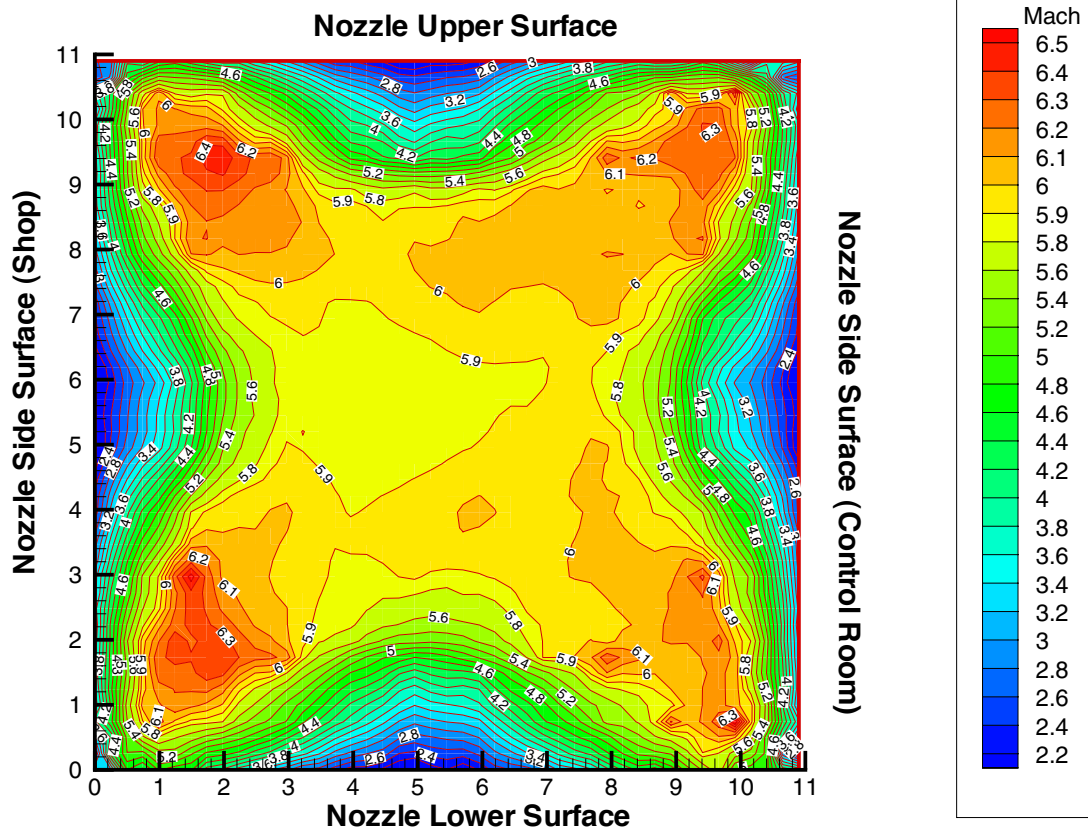


Figure 16m. Mach contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

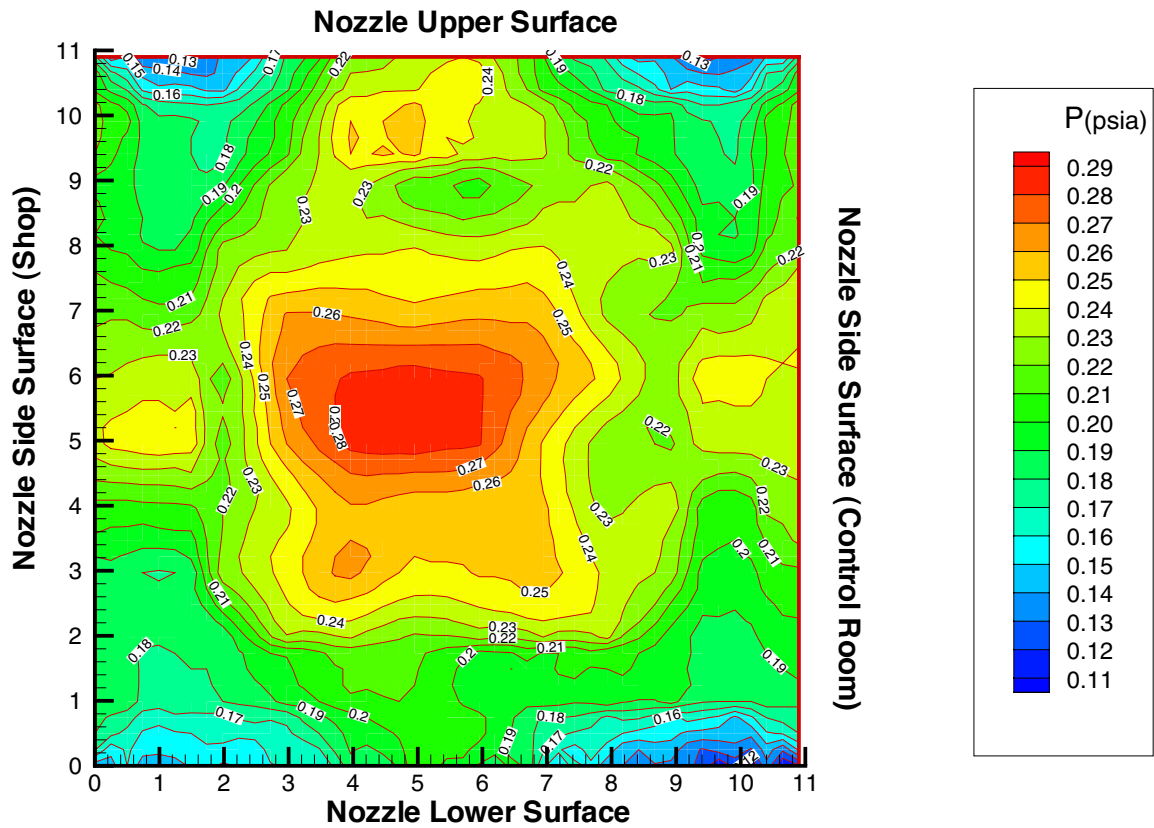


Figure 16n. Static pressure contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

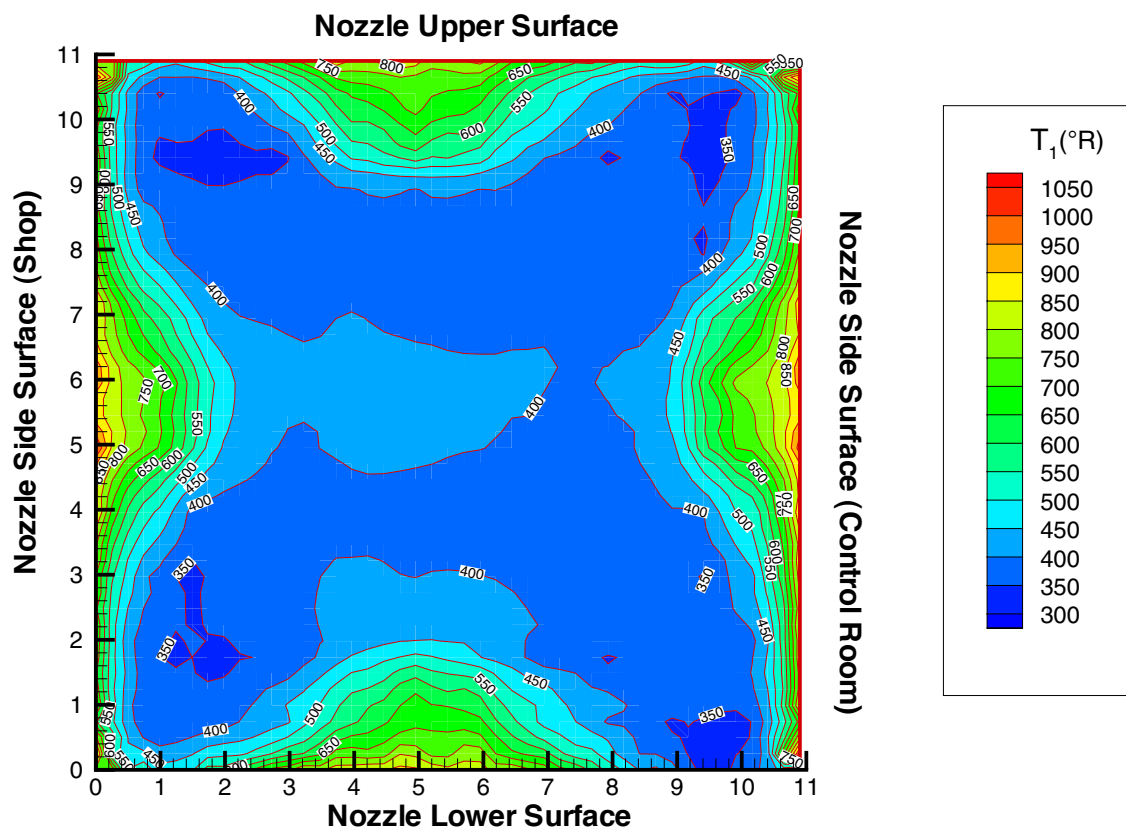


Figure 16o. Static temperature contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

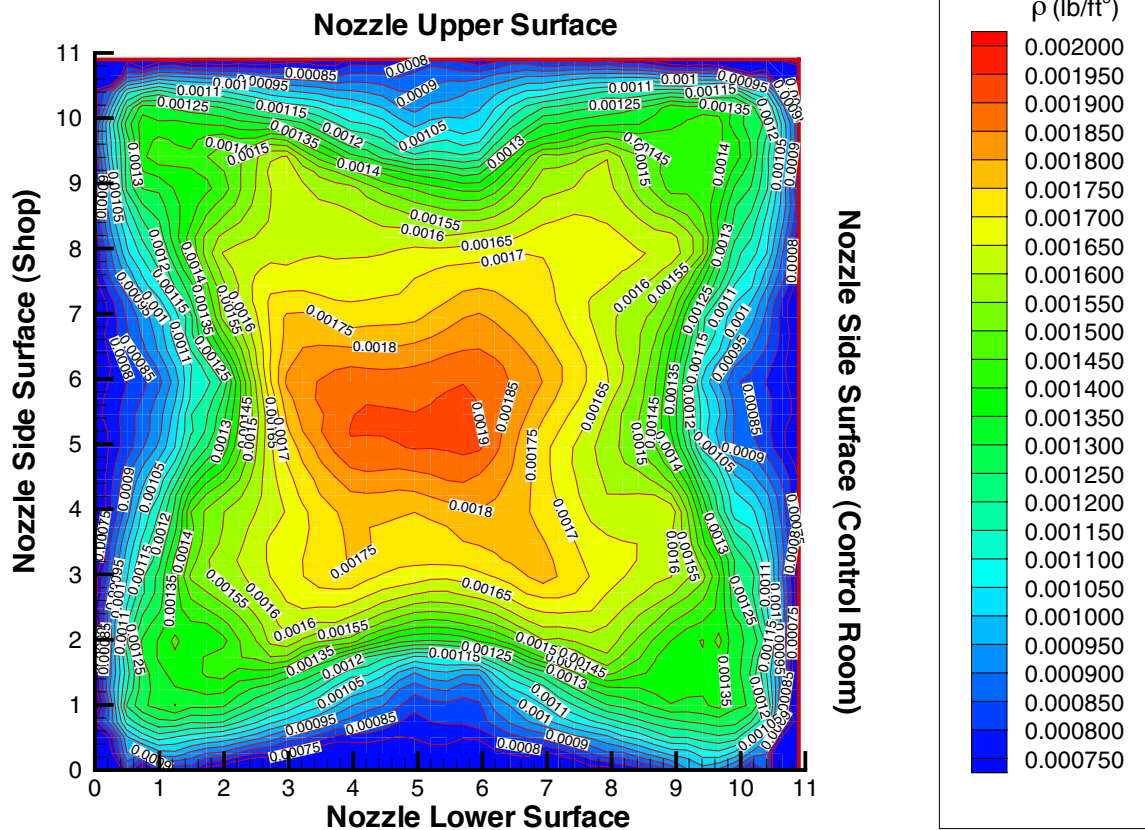


Figure 16p. Static density contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

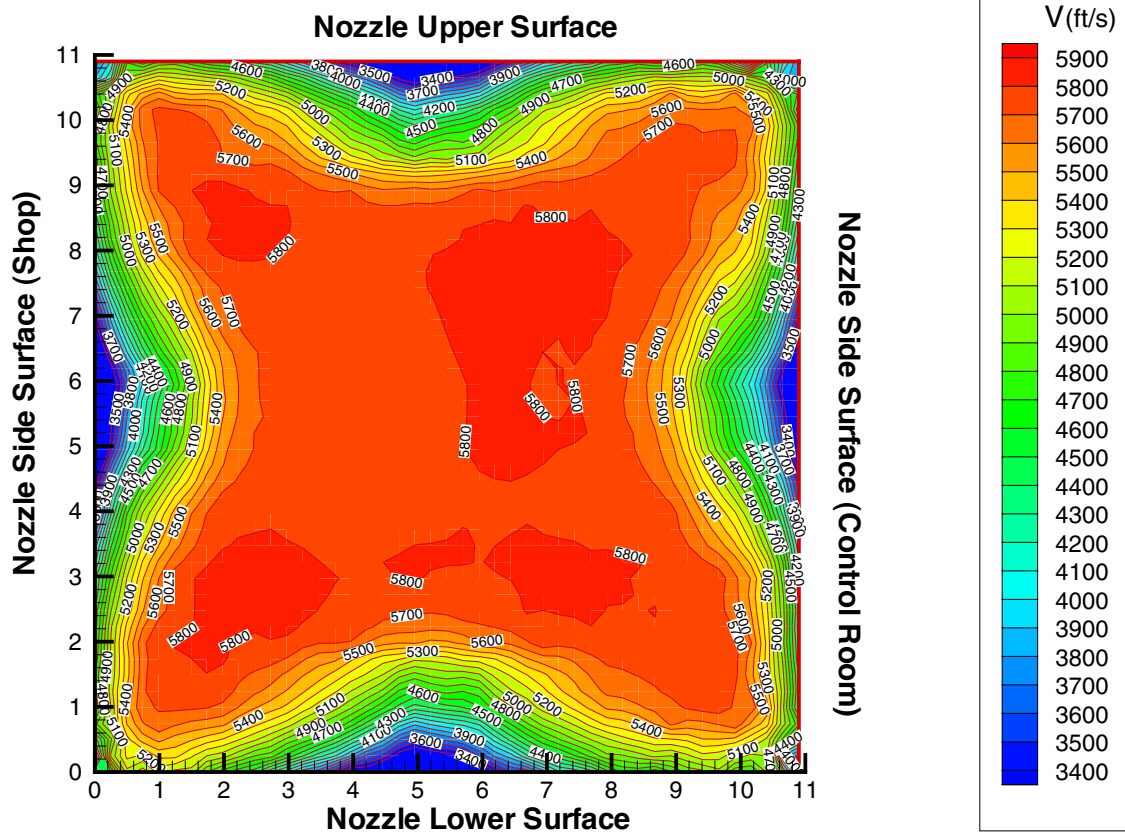


Figure 16q. Velocity contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

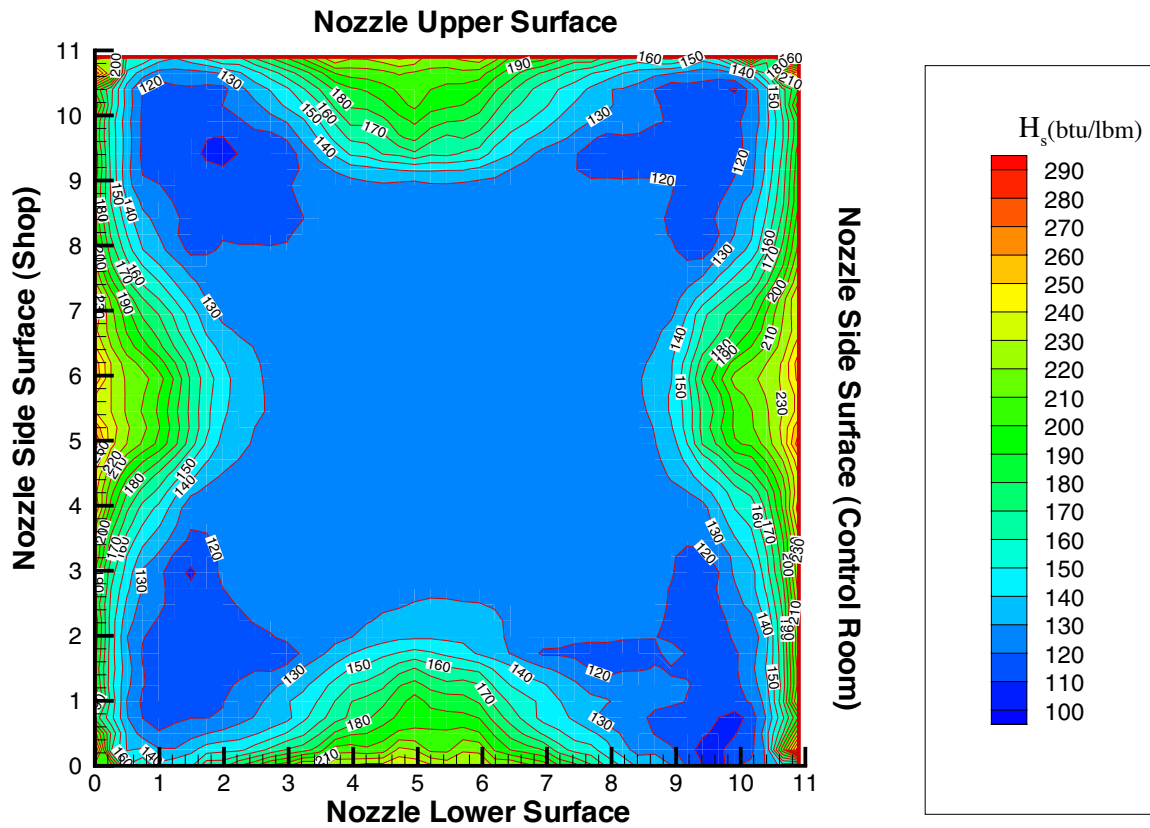


Figure 16r. Static enthalpy contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

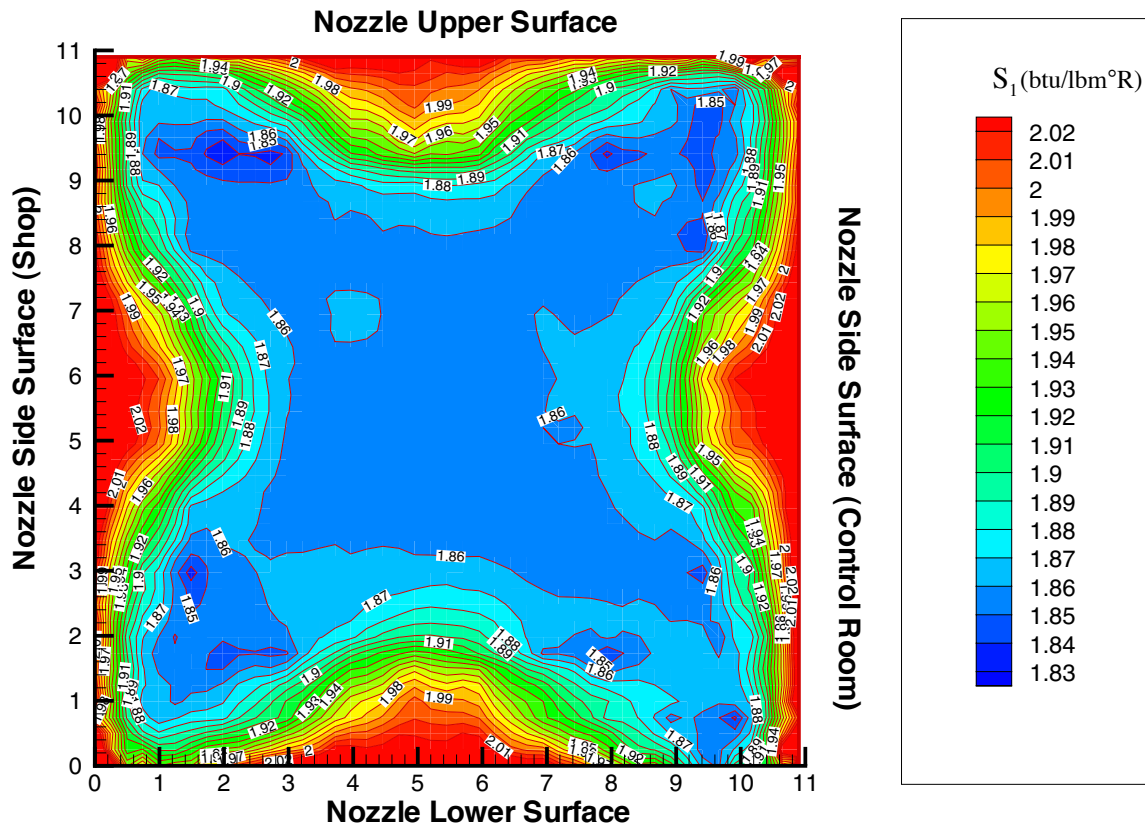


Figure 16s. Entropy contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

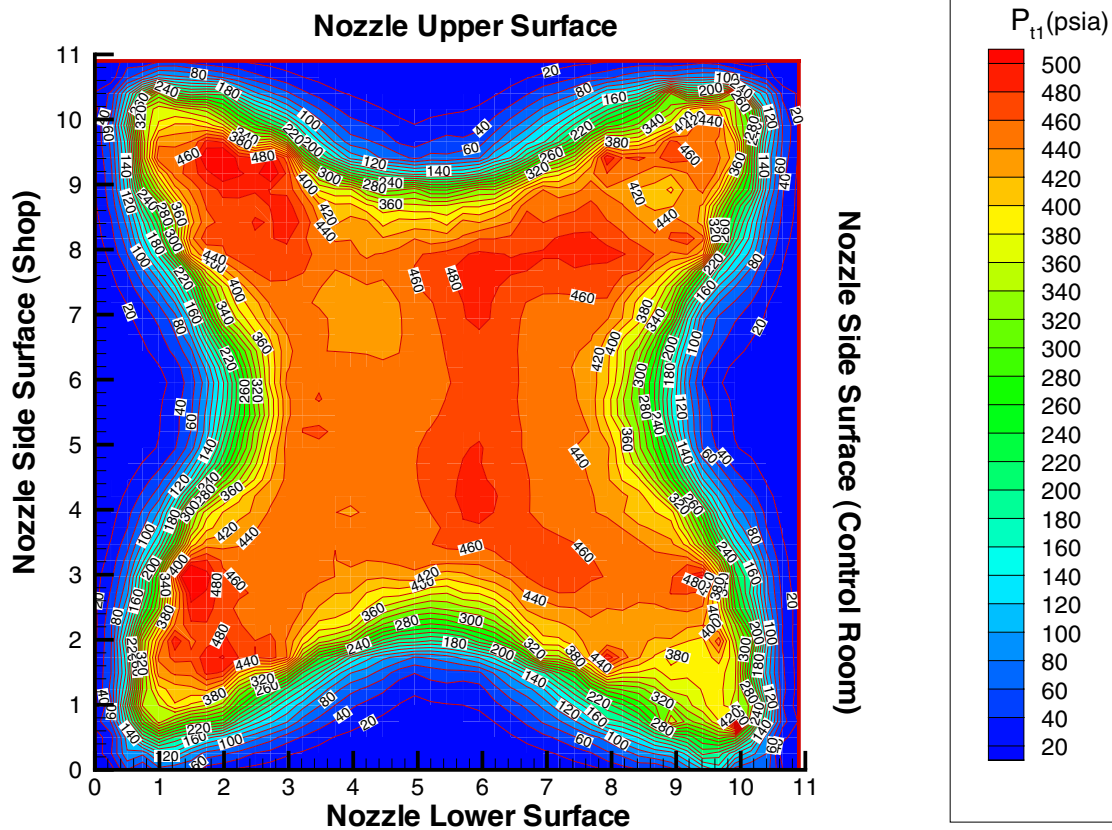


Figure 16t. Freestream total pressure contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

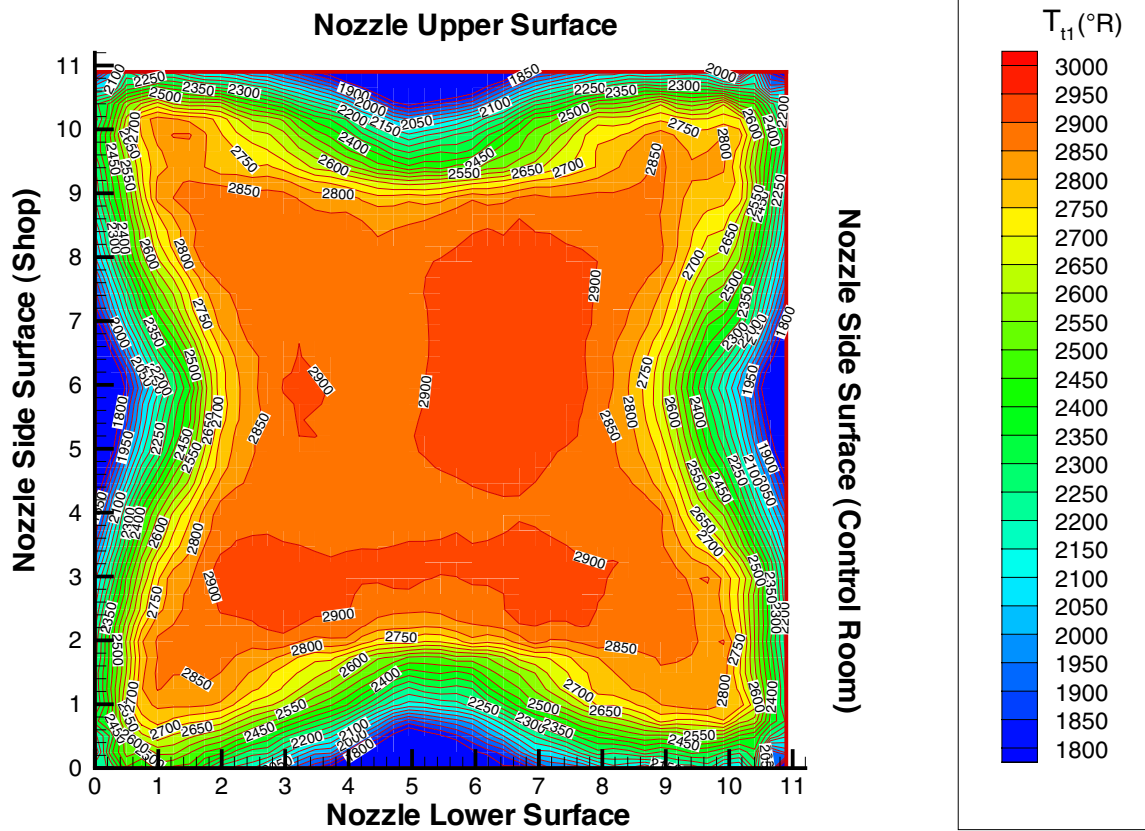


Figure 16u. Freestream total temperature contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

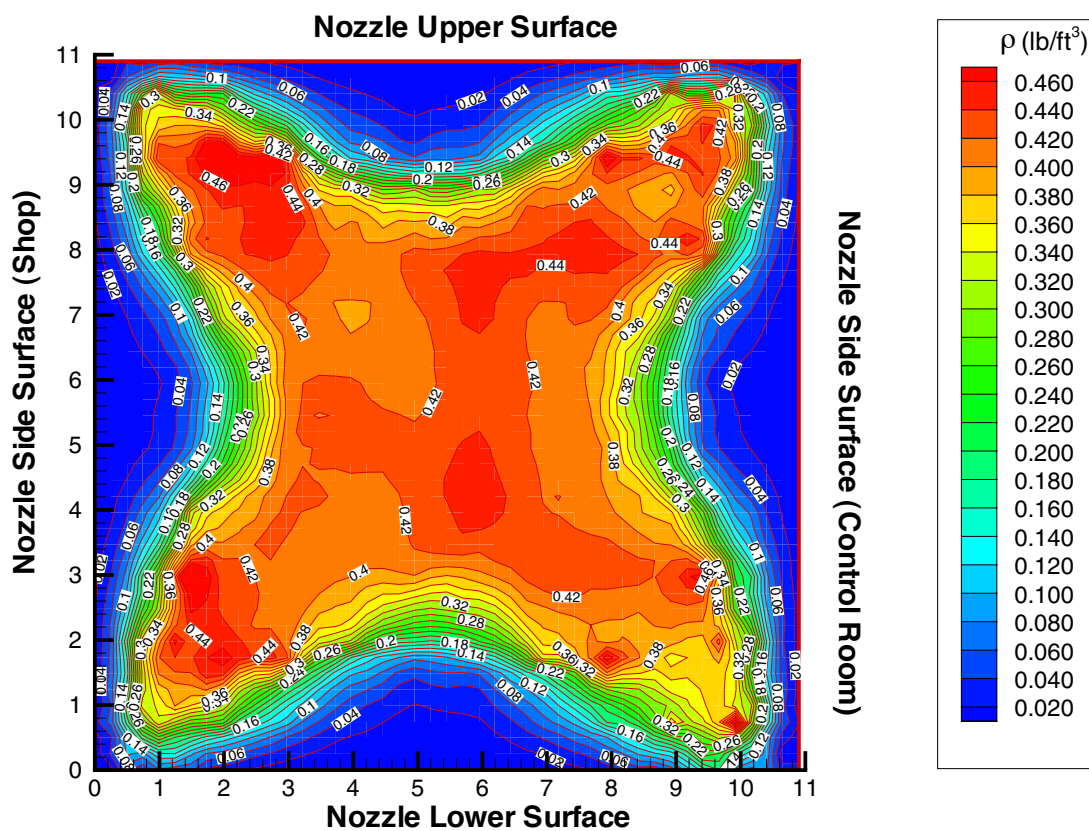


Figure 16v. Freestream total density contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 6 enthalpy test point (PT1 = 495 psia, HST = 795 btu/lbm). All dimensions are in inches.

Mach 6 Nozzle, Mach 7 Enthalpy, Test Condition

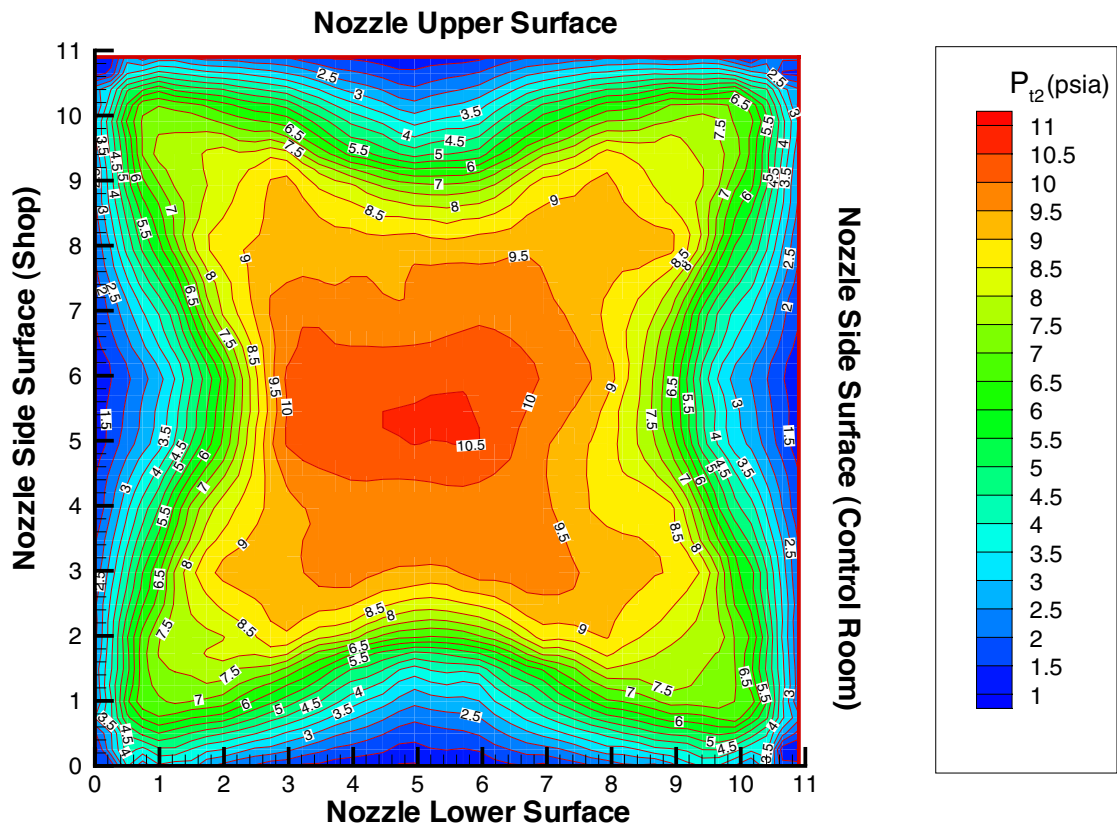


Figure 17a. Pitot pressure contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

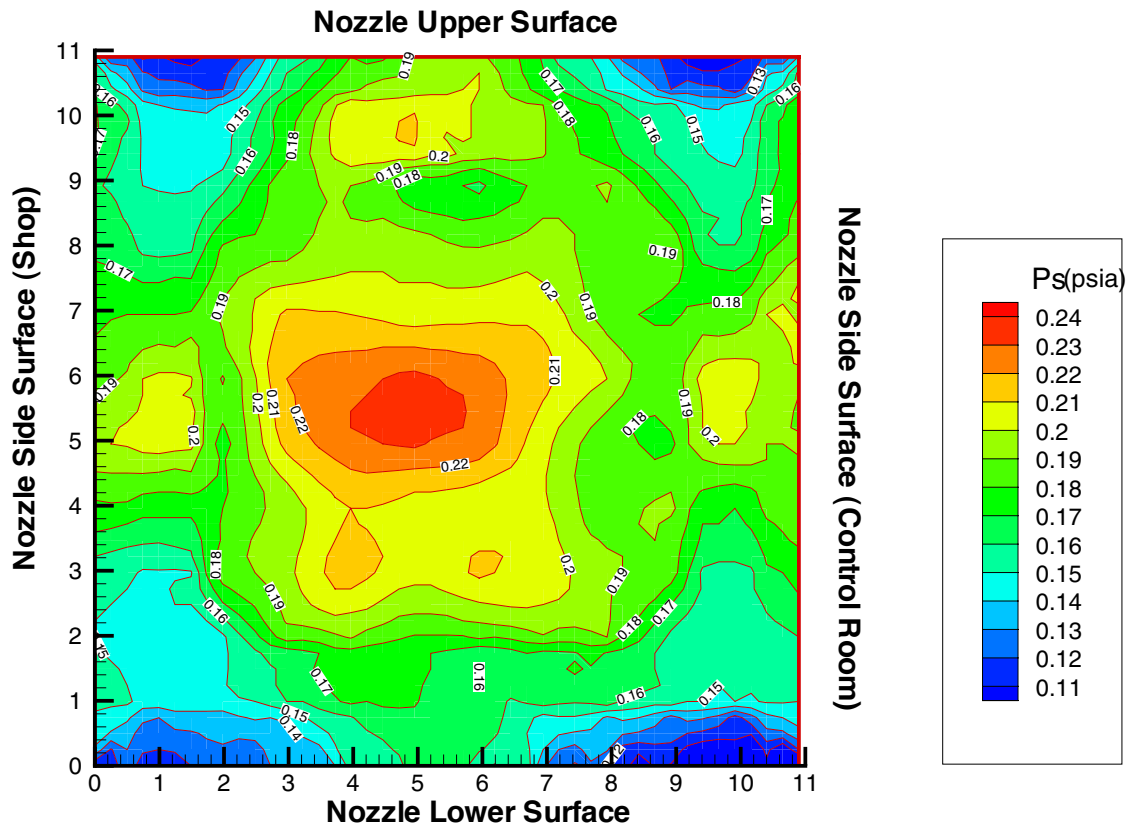


Figure 17b. Static pressure contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

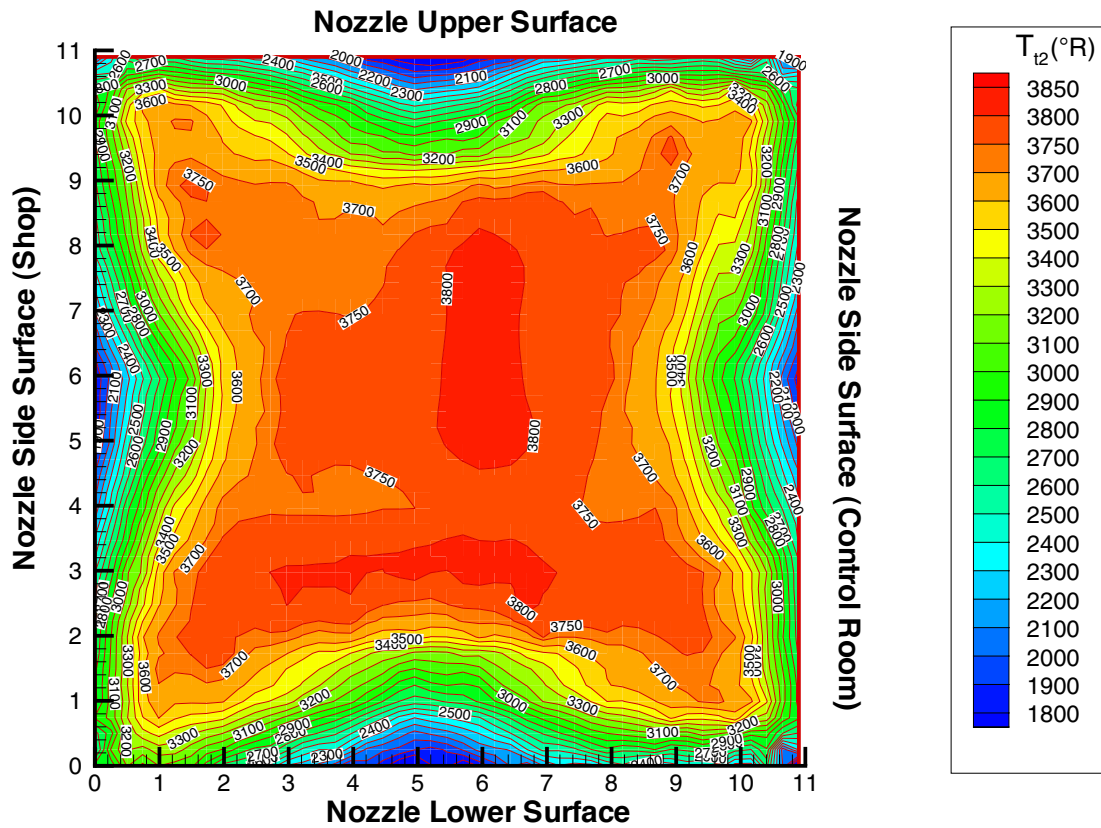


Figure 17c. Total temperature contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

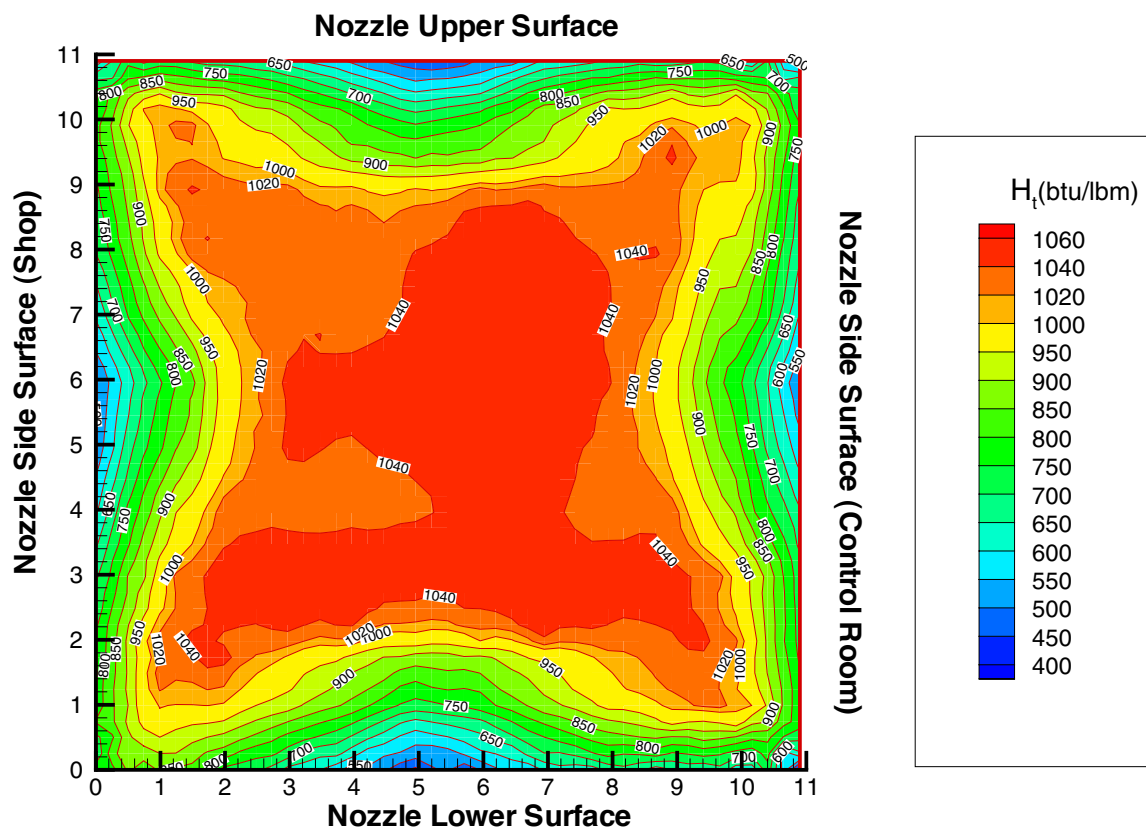


Figure 17d. Total enthalpy contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

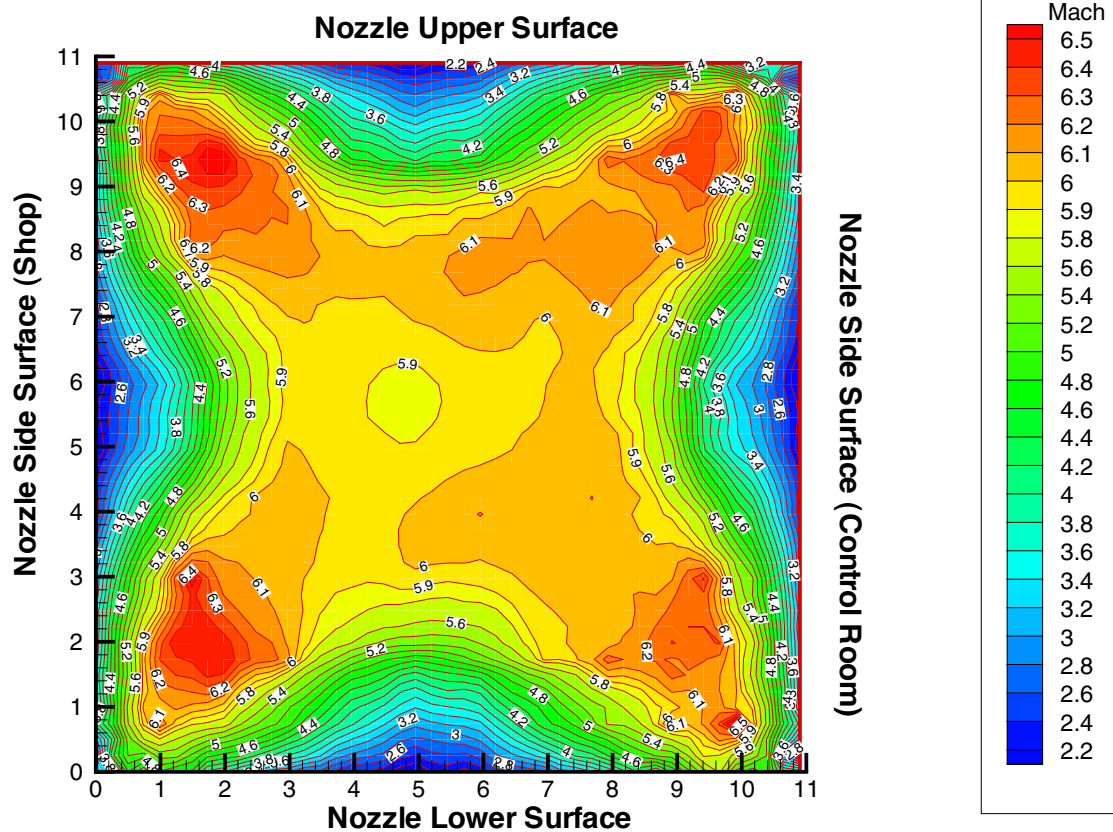


Figure 17e. Mach contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

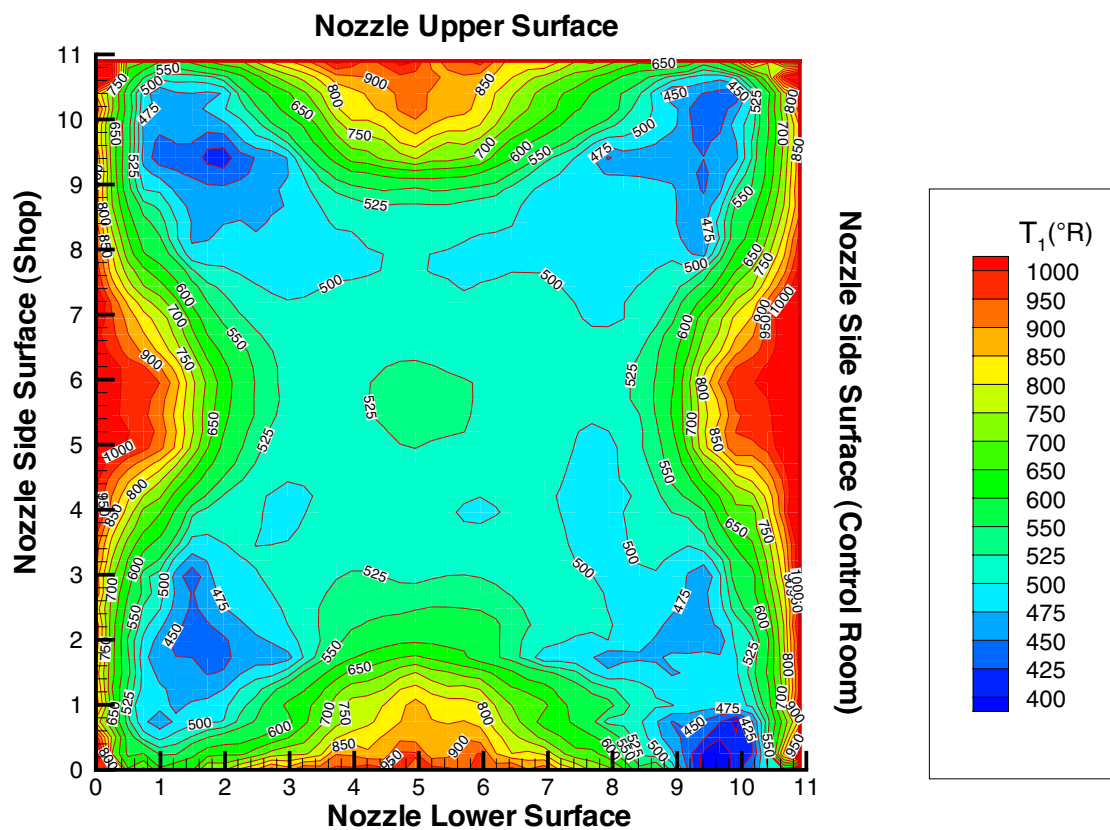


Figure 17f. Static temperature contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

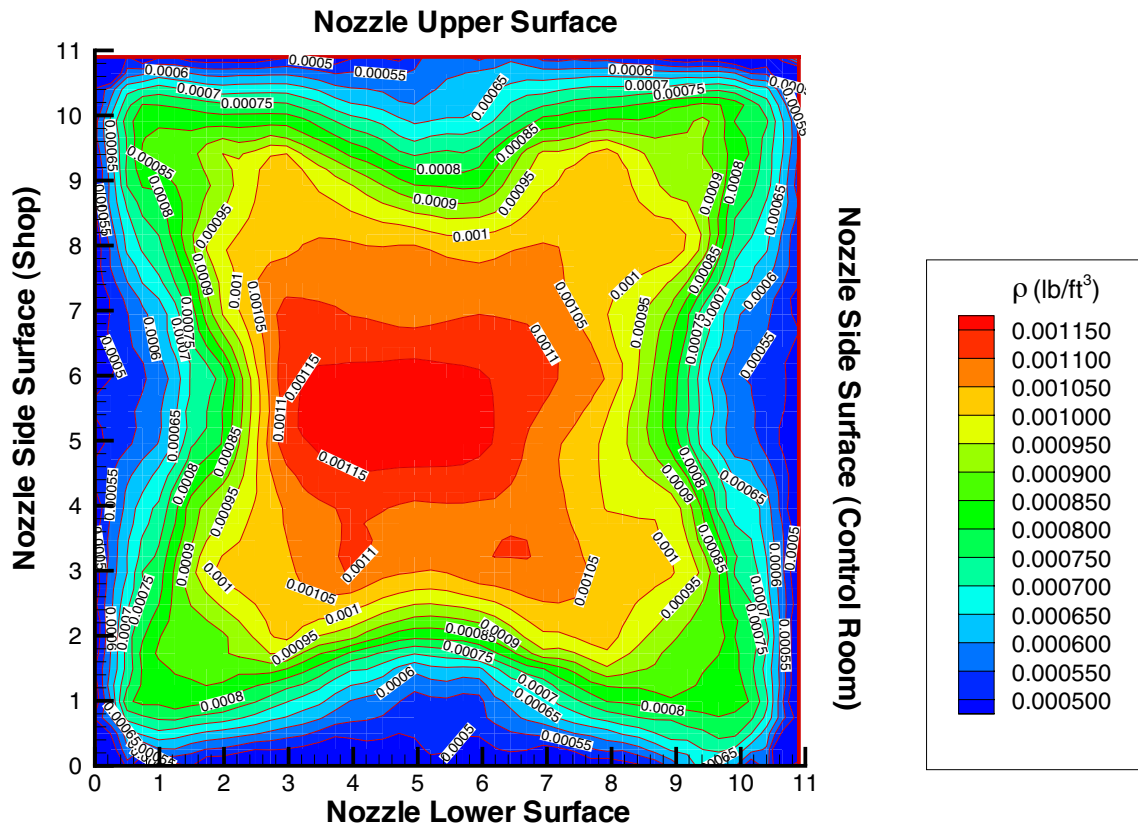


Figure 17g. Static density contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

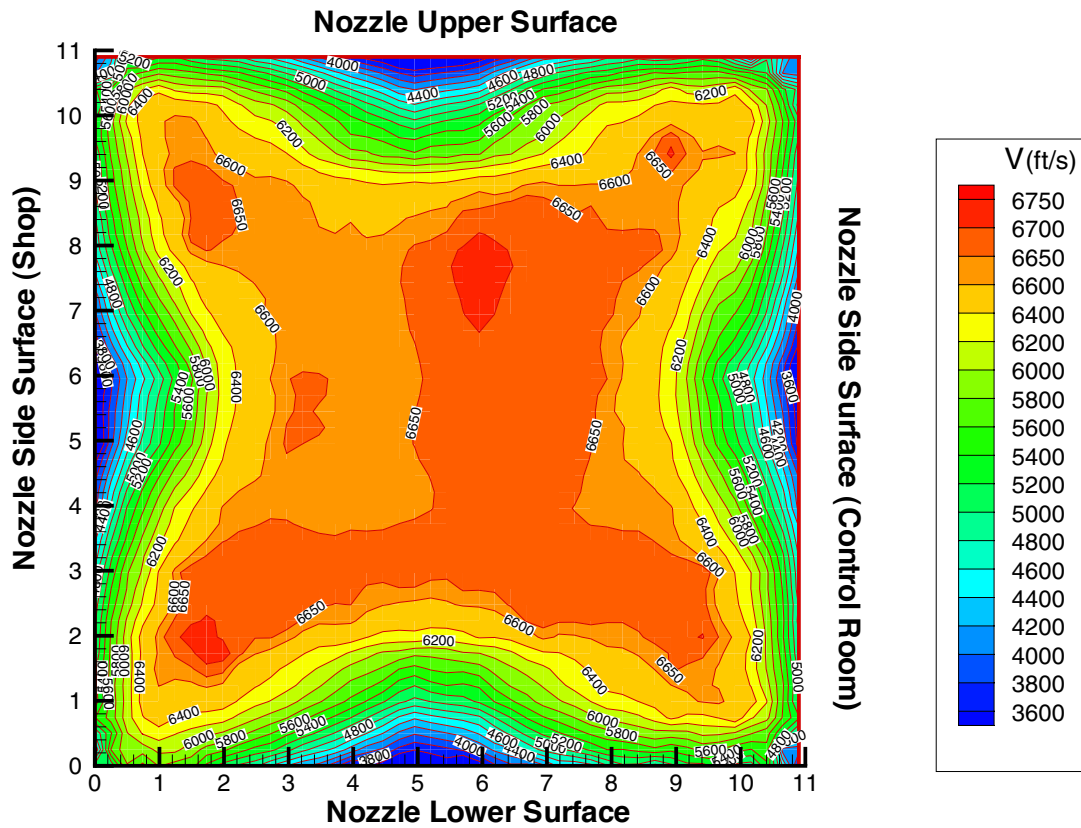


Figure 17h. Velocity contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

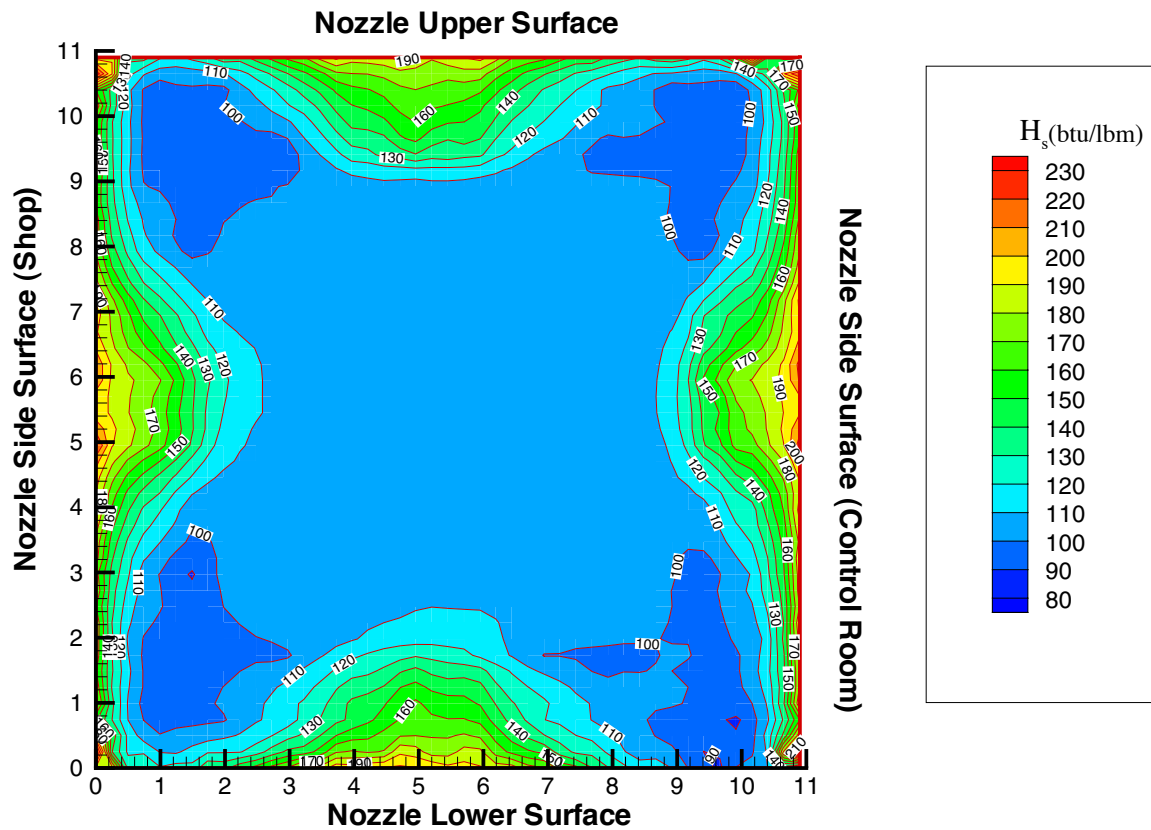


Figure 17i. Static enthalpy contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

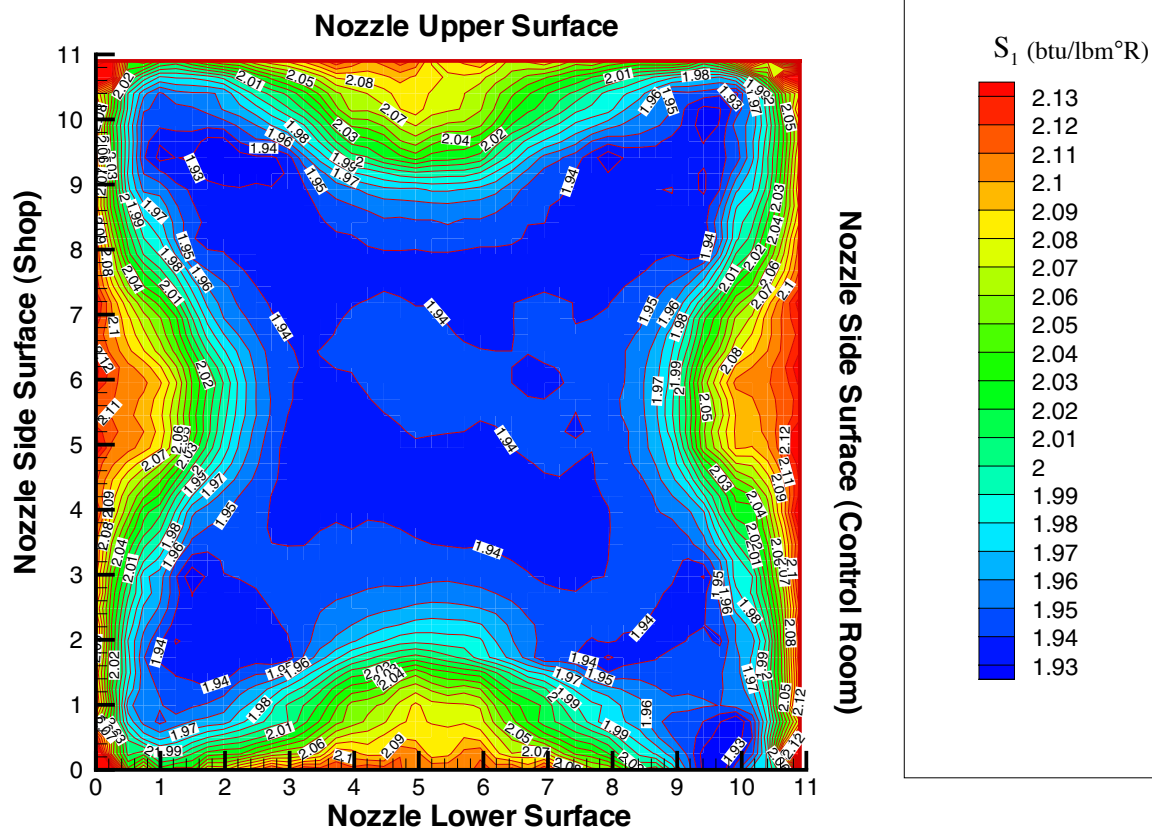


Figure 17j. Entropy contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

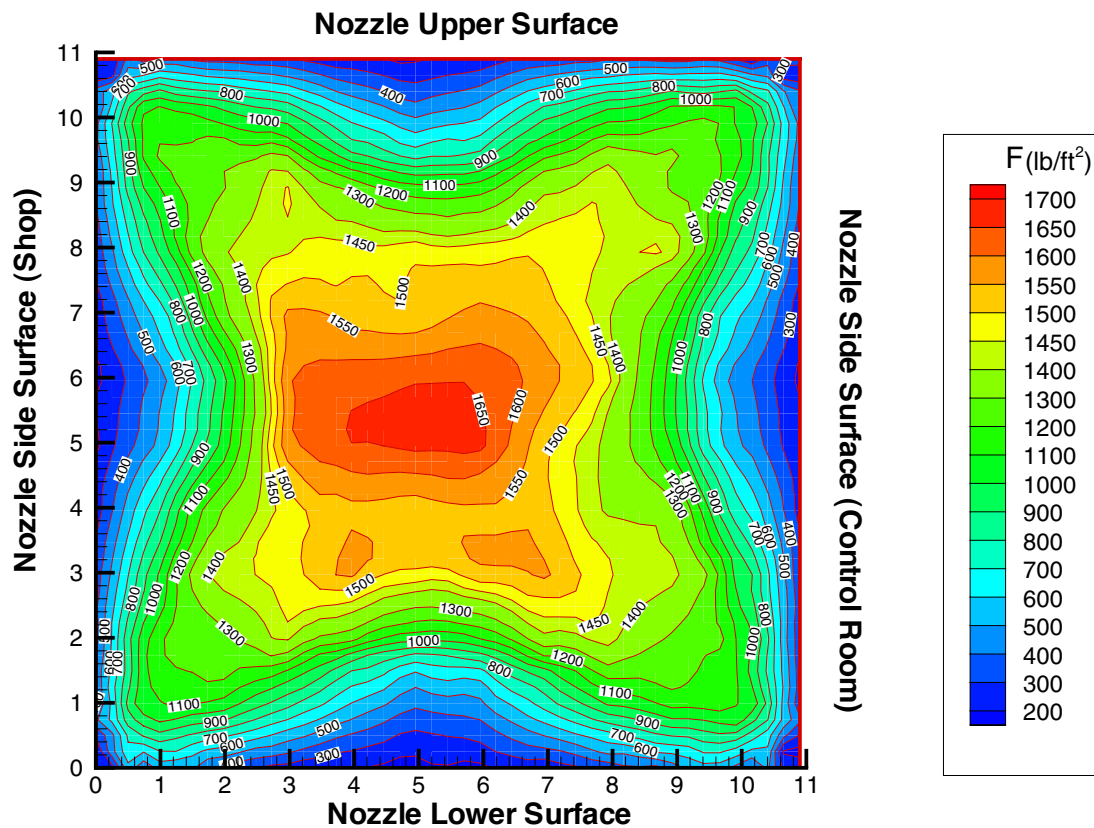


Figure 17k. Stream thrust contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

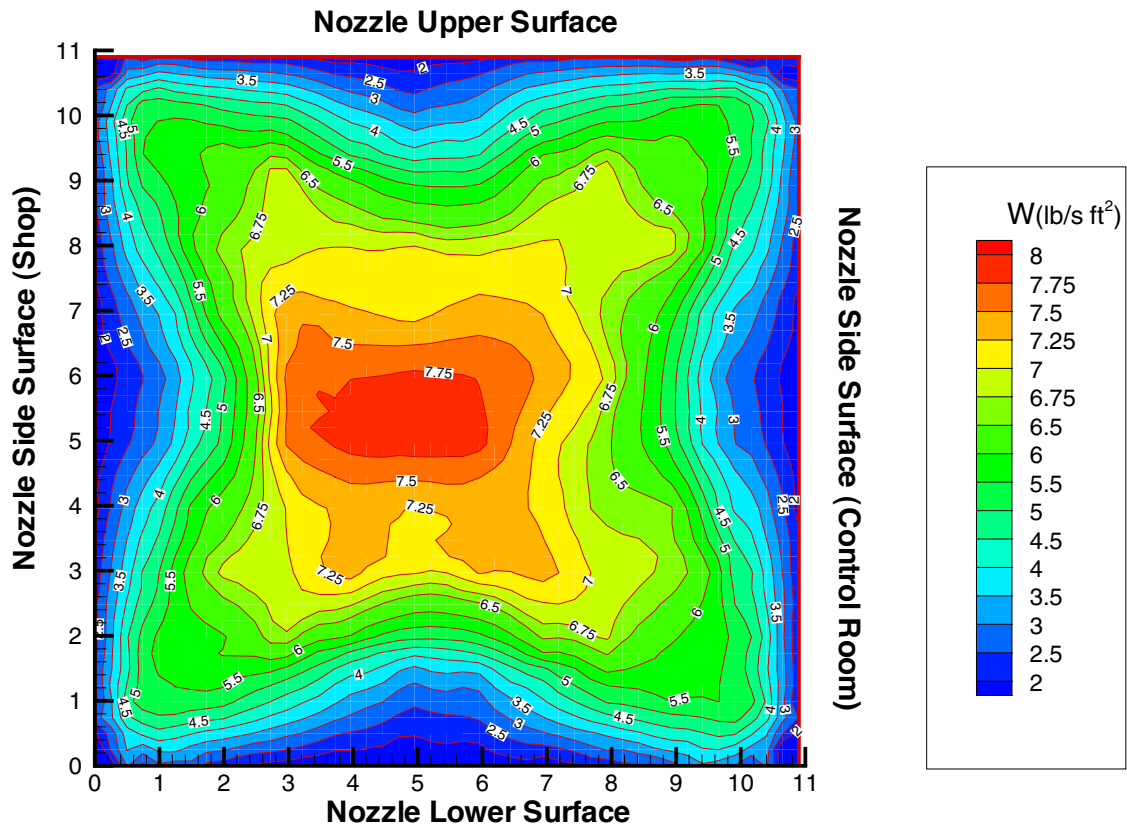


Figure 17I. Mass flux contours (vibrationally frozen) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

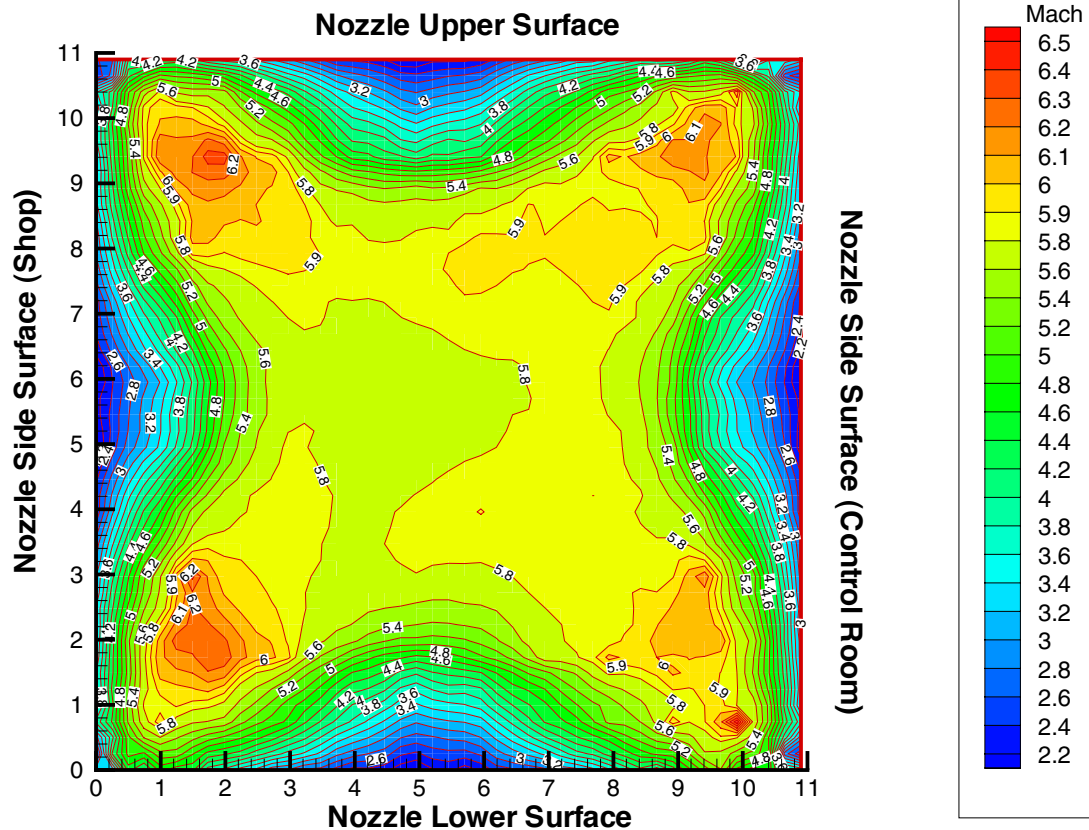


Figure 17m. Mach contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

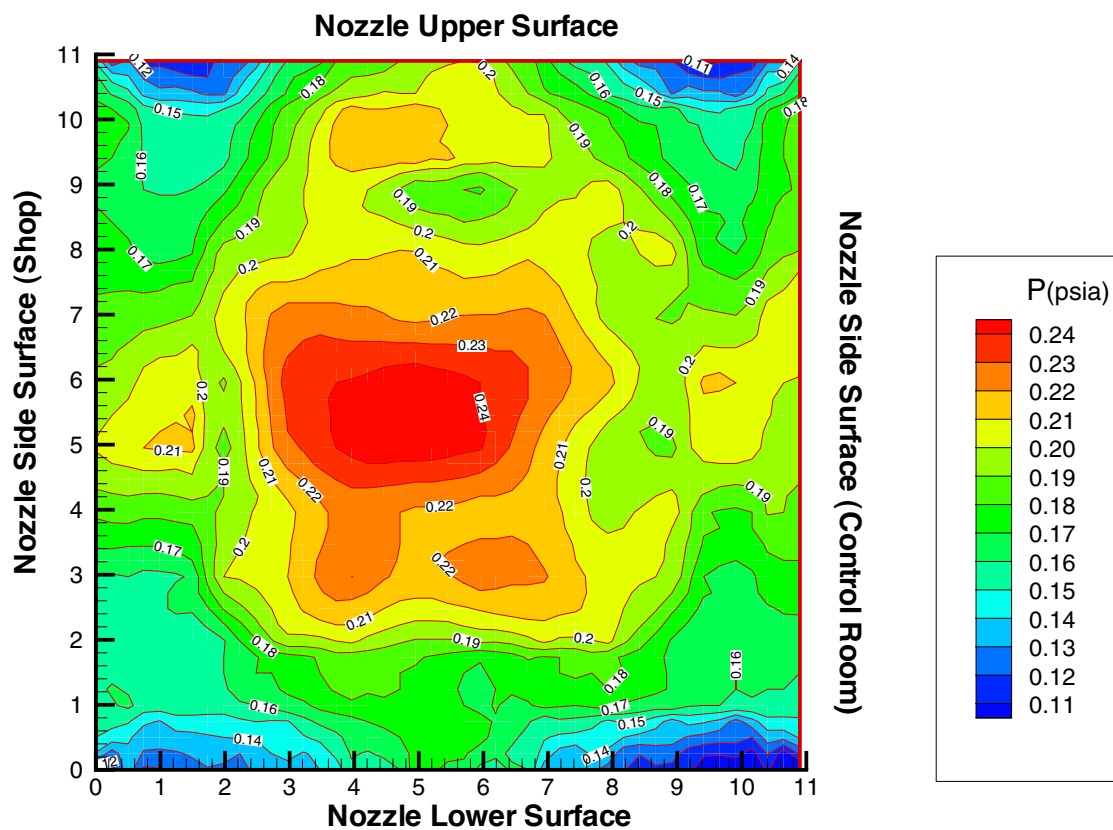


Figure 17n. Static pressure contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

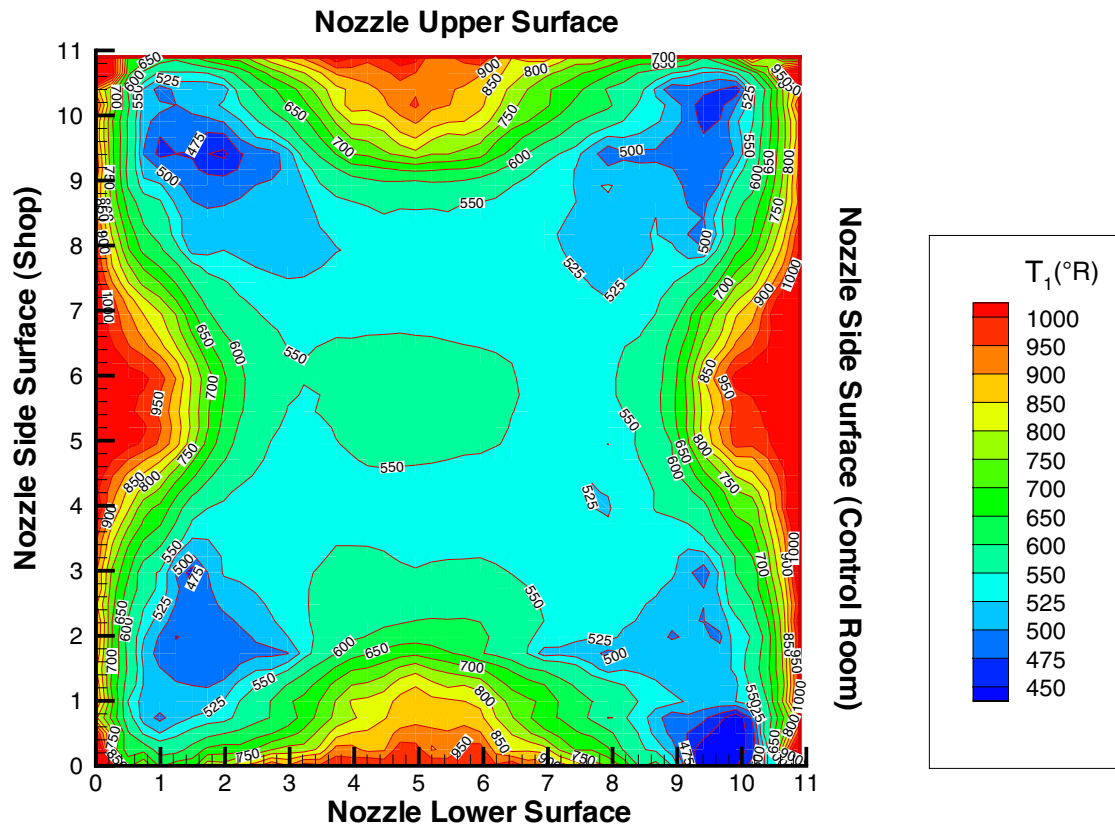


Figure 17o. Static temperature contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

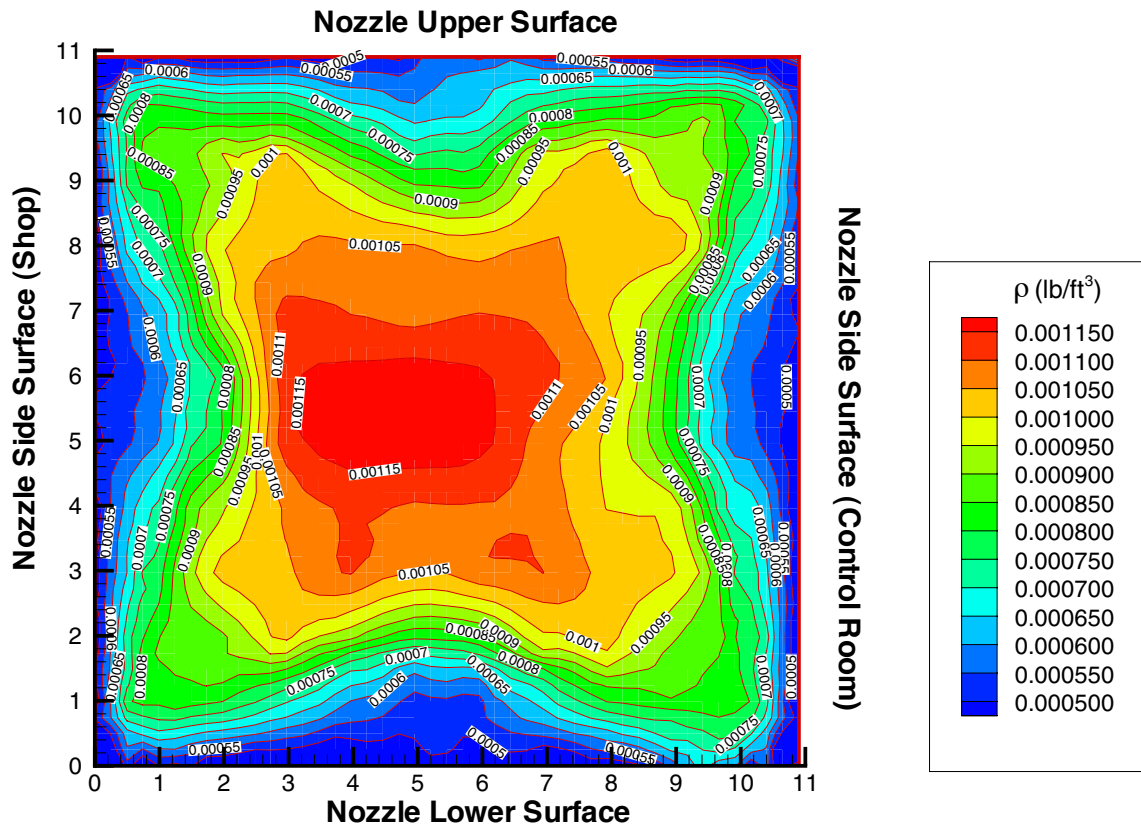


Figure 17p. Static density contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

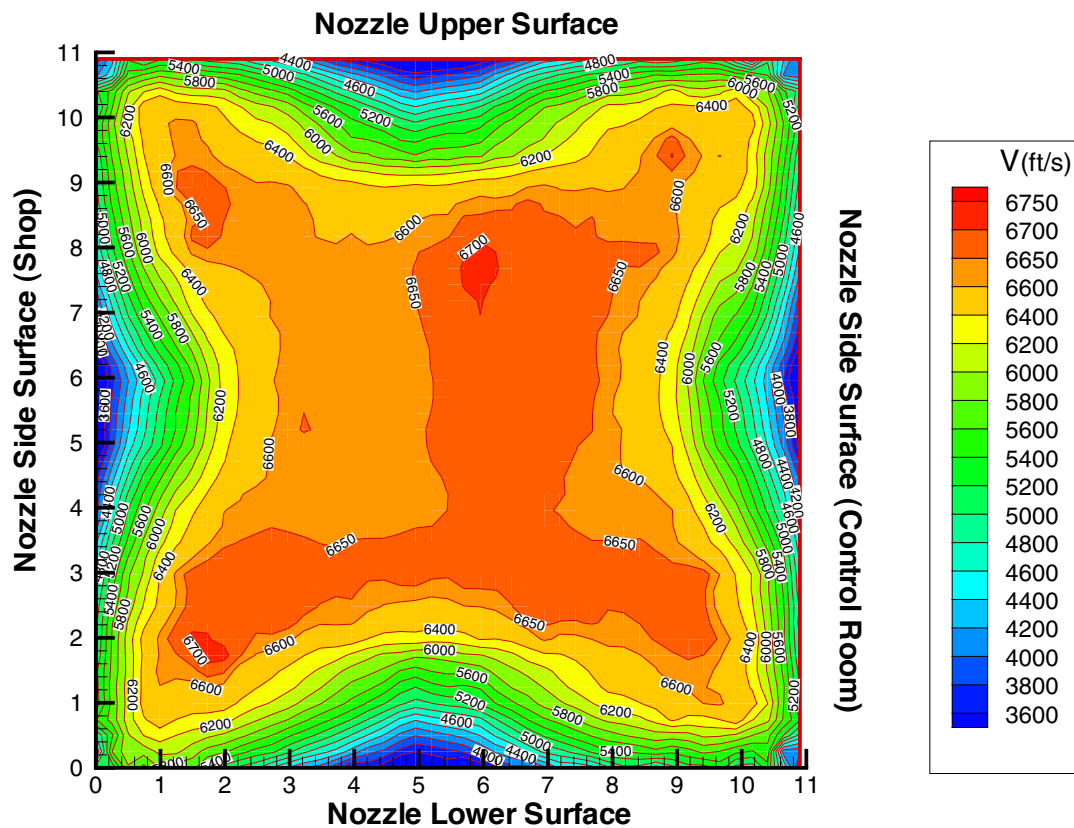


Figure 17q. Velocity contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

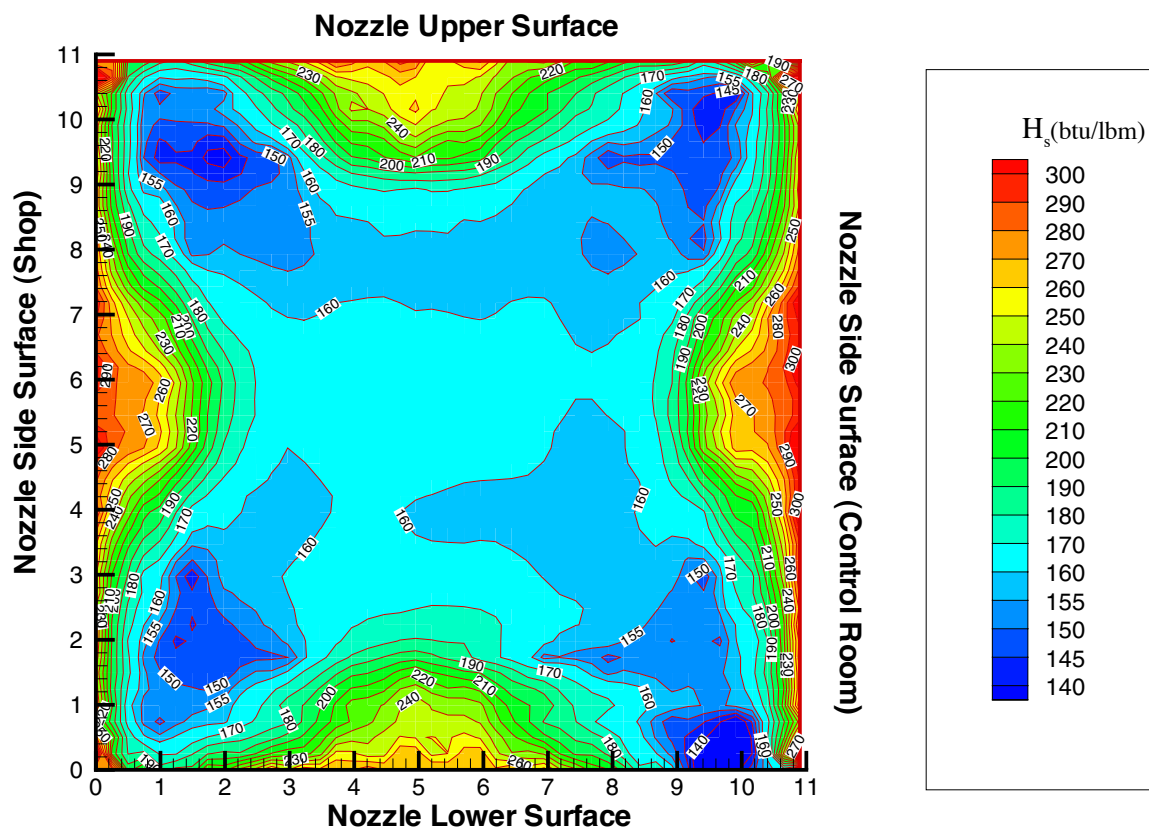


Figure 17r. Static enthalpy contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

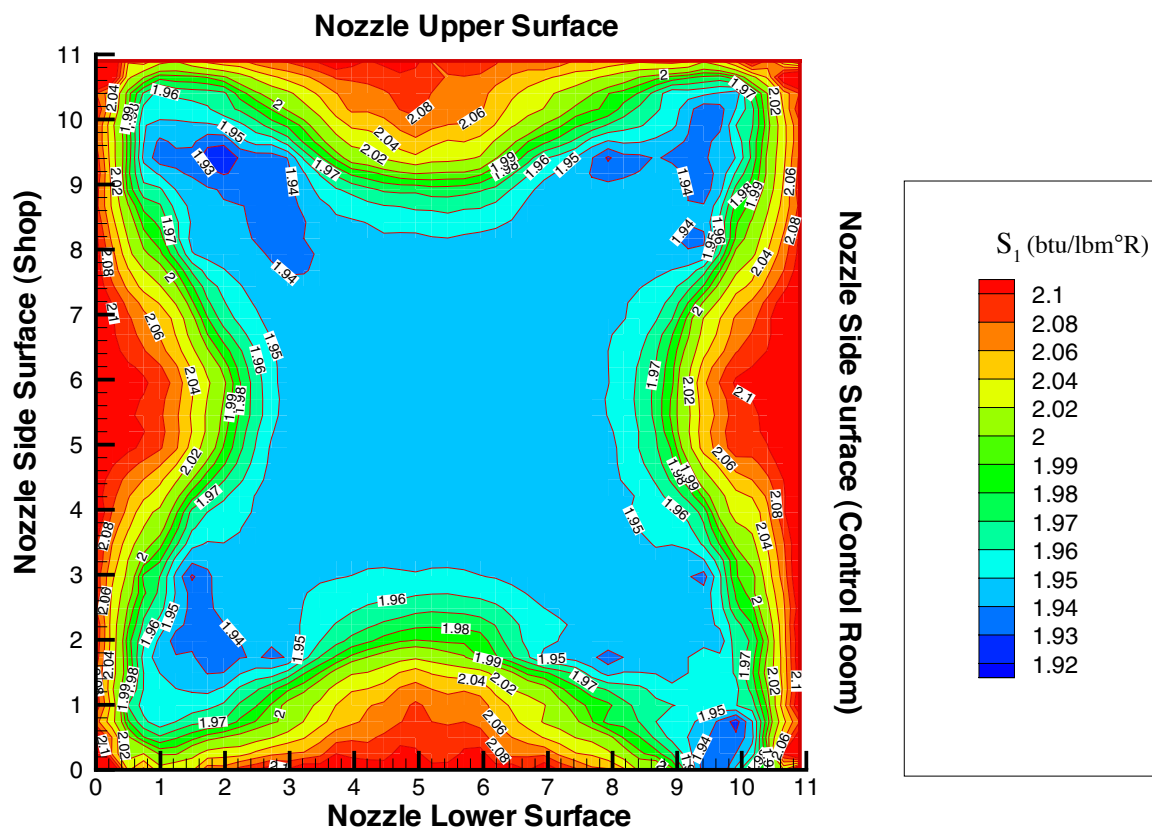


Figure 17s. Entropy contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

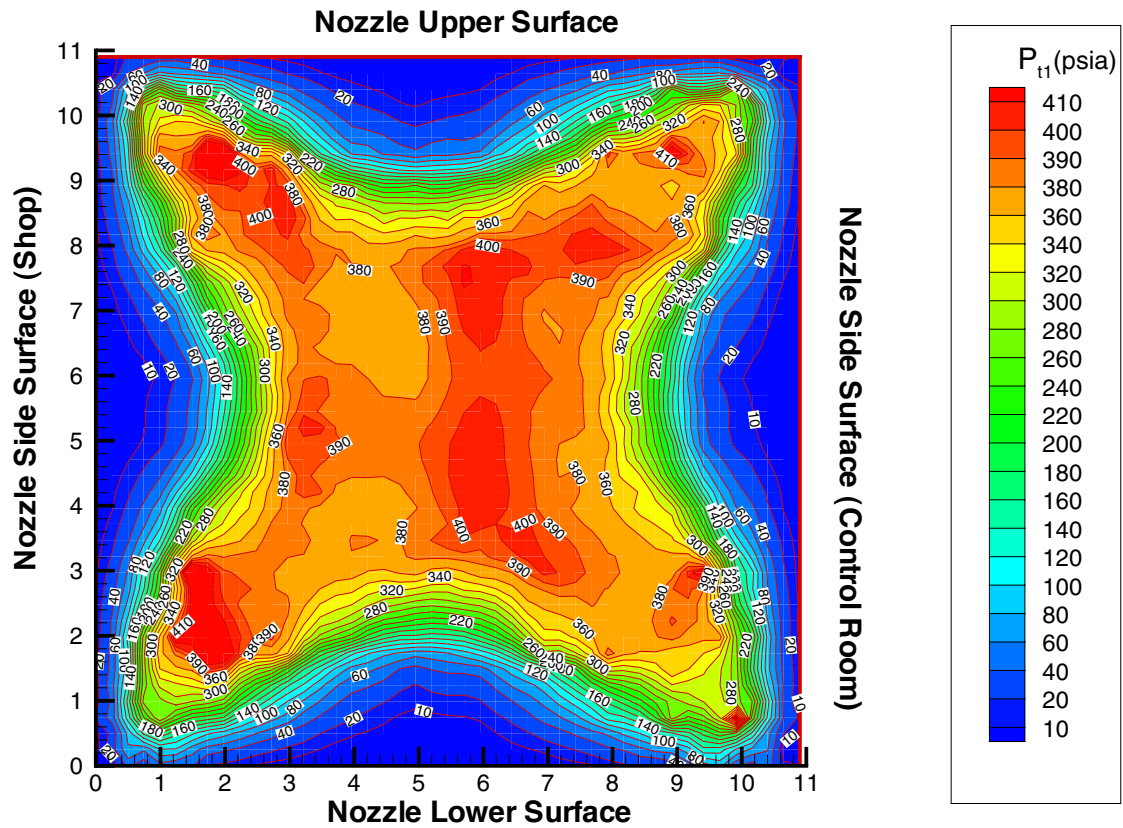


Figure 17t. Freestream total pressure contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

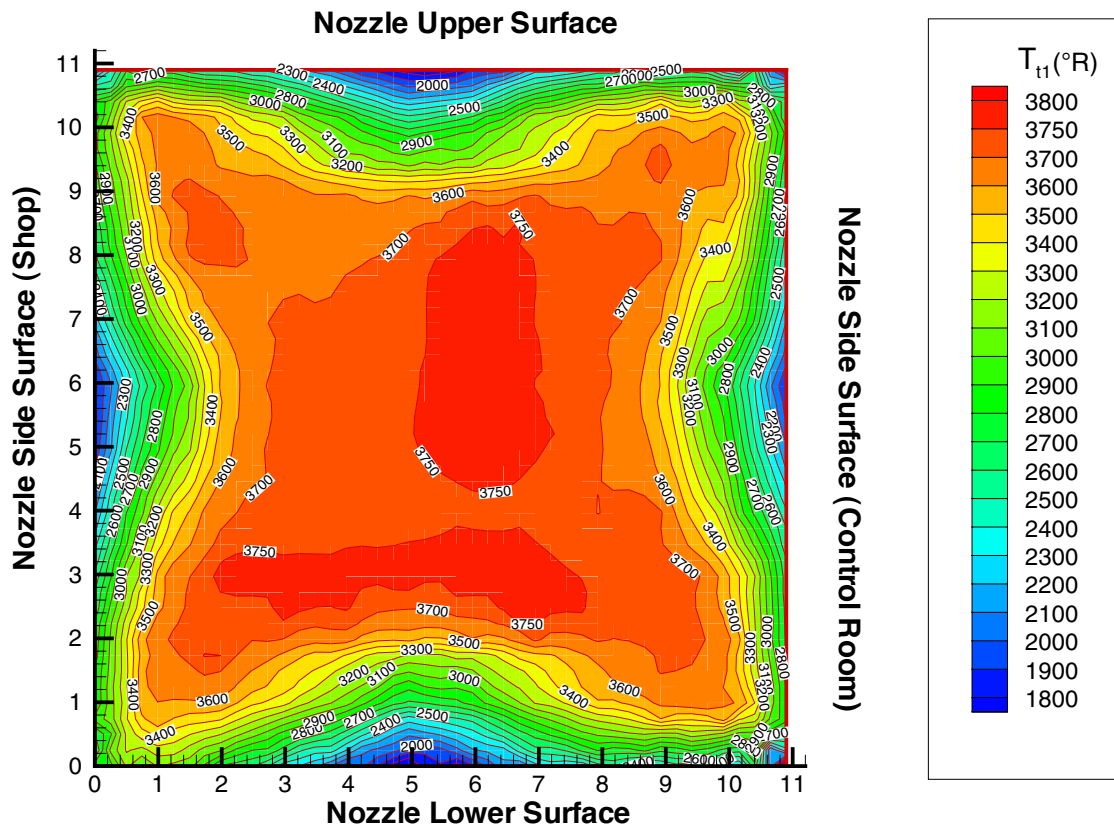


Figure 17u. Freestream total temperature contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

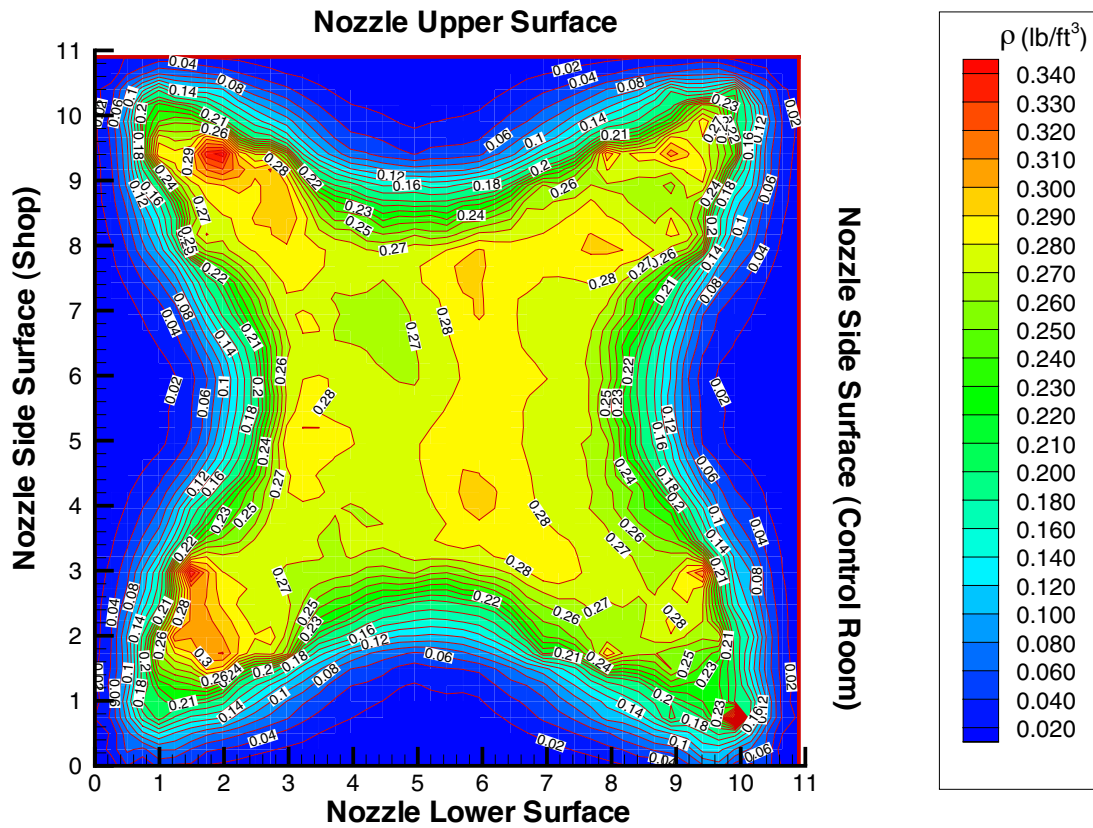


Figure 17v. Freestream total density contours (vibrationally relaxed) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

Comparison with 1986 AHSTF Mach 6 Nozzle Calibration, Mach 7 Enthalpy, Test Condition

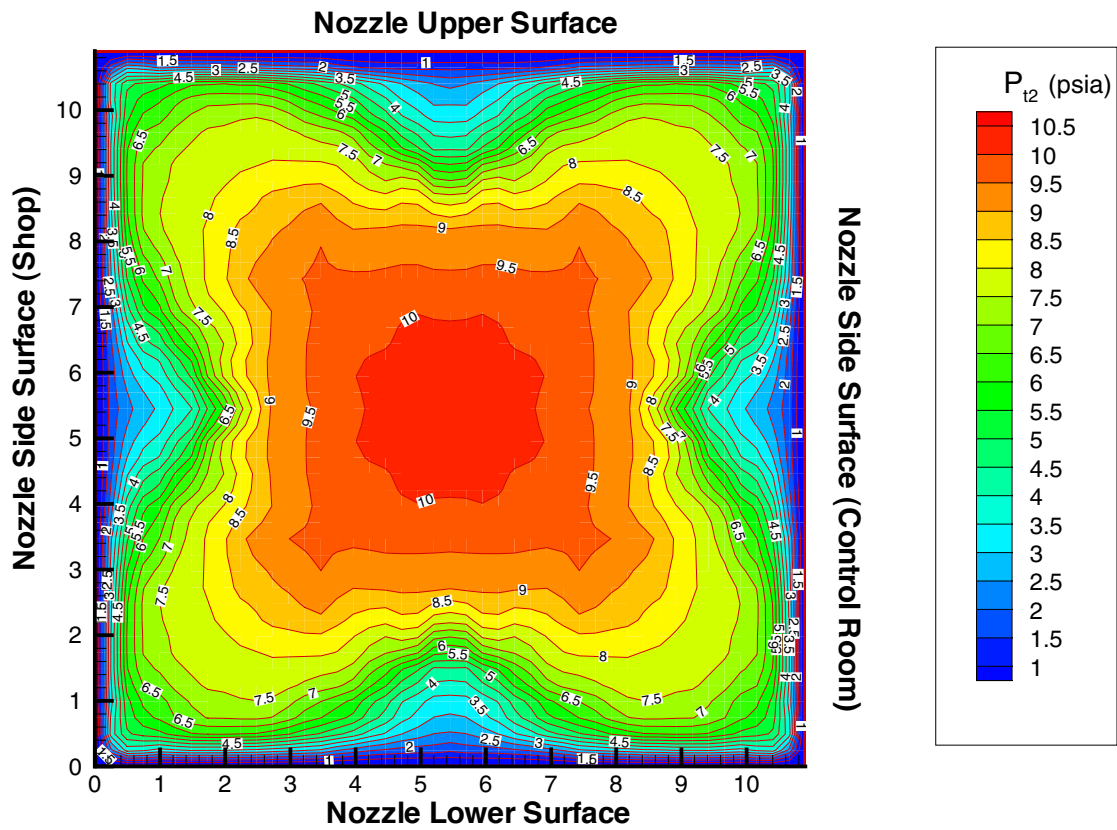


Figure 18a. 1986 pitot pressure contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point ($PT1 = 410$ psia, $HST = 1040$ btu/lbm). All dimensions are in inches.

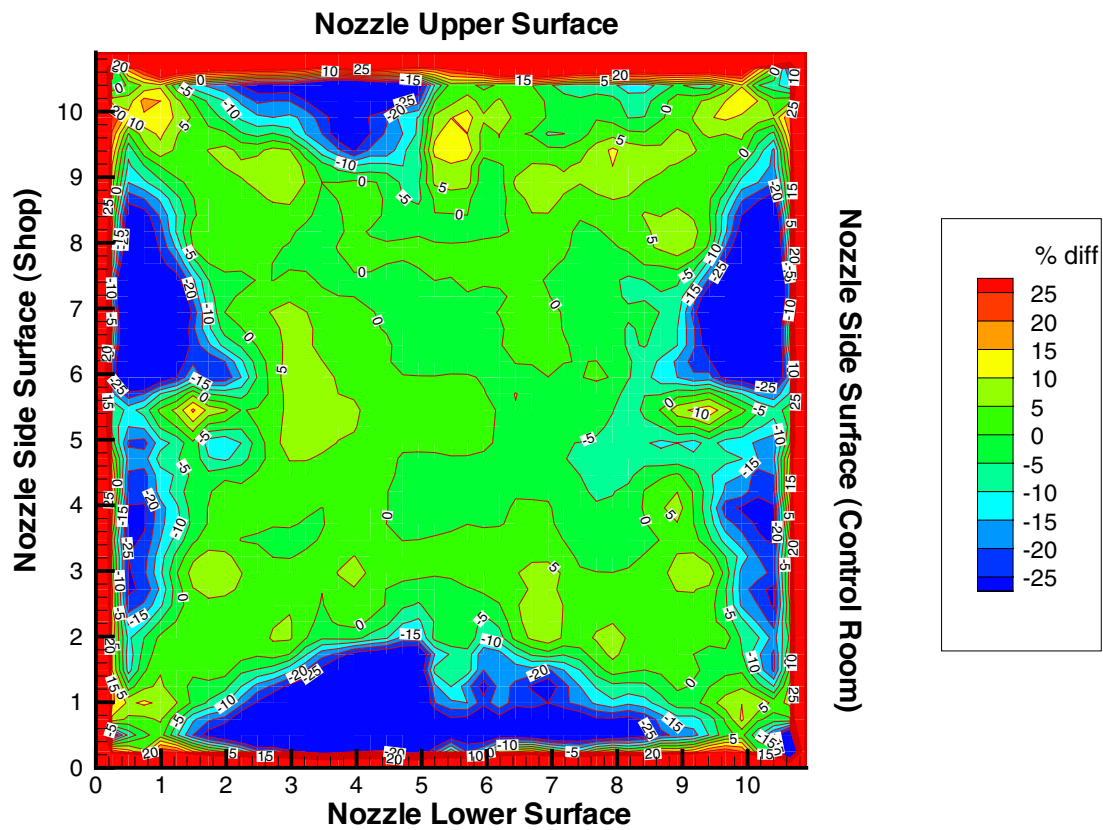


Figure 18b. 1986/1998 pitot pressure delta contours at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

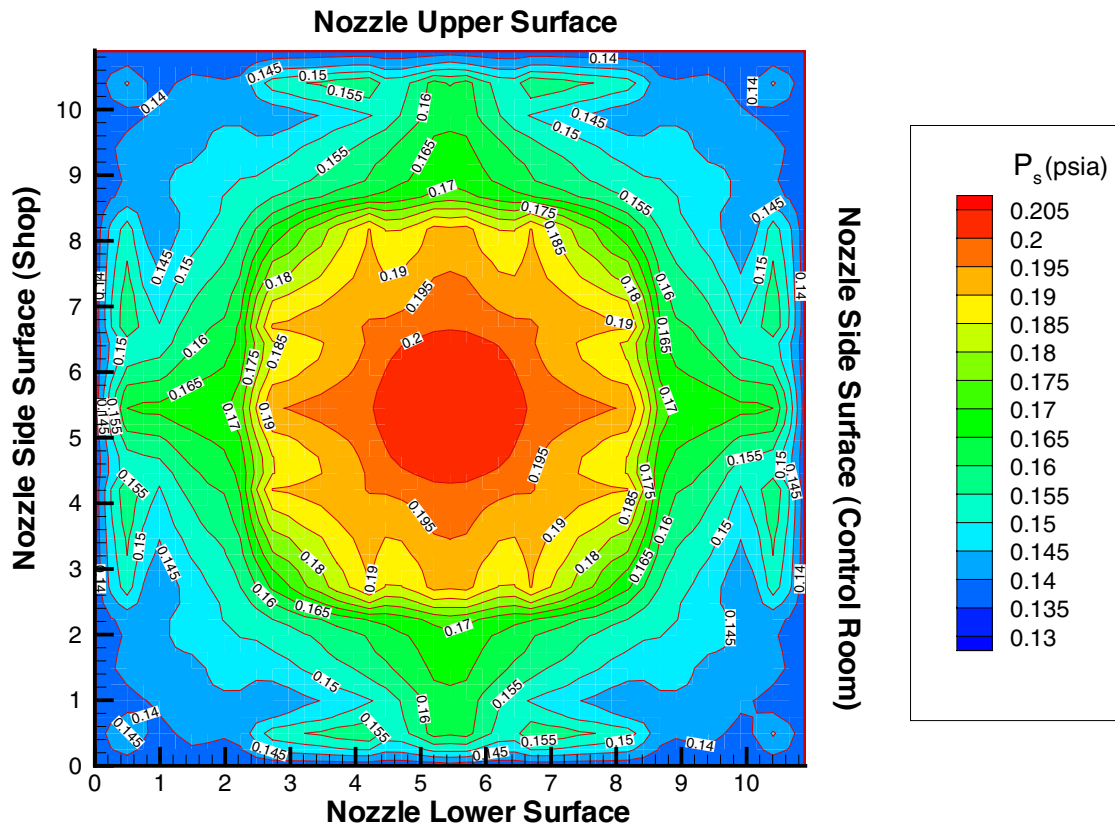


Figure 18c. 1986 static pressure contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

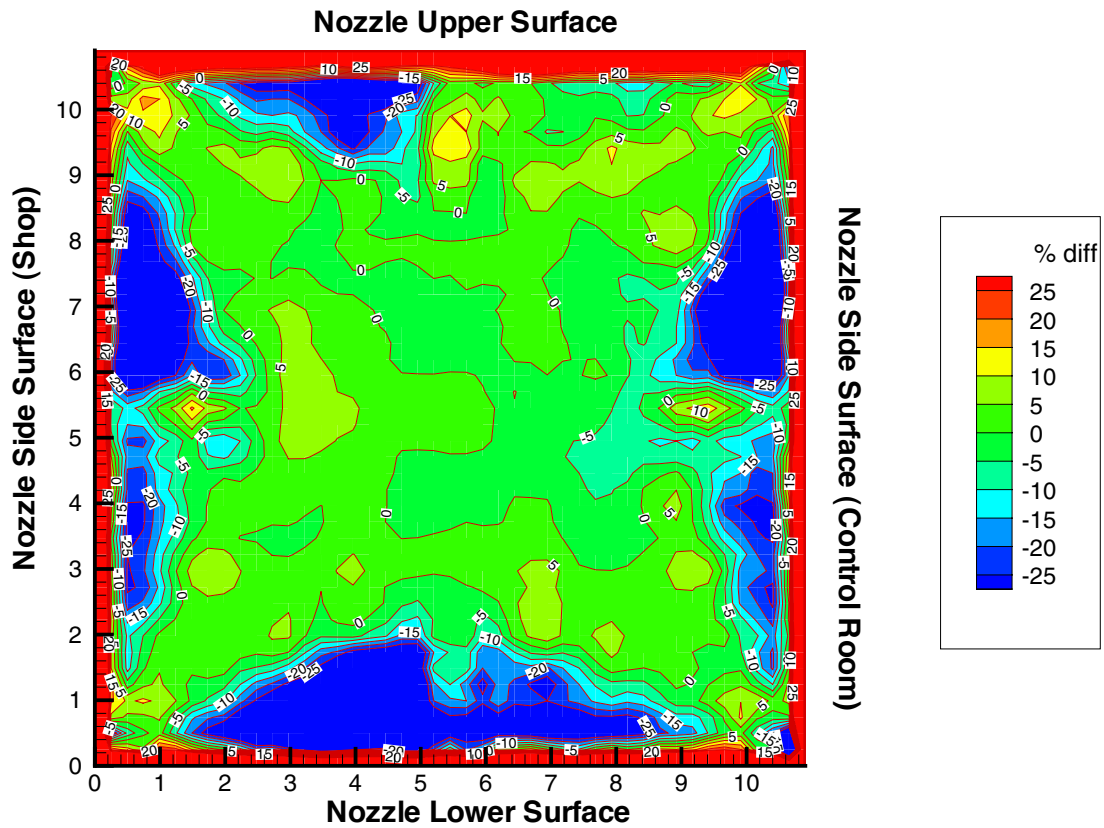


Figure 18d. 1986/1998 static pressure delta contours at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

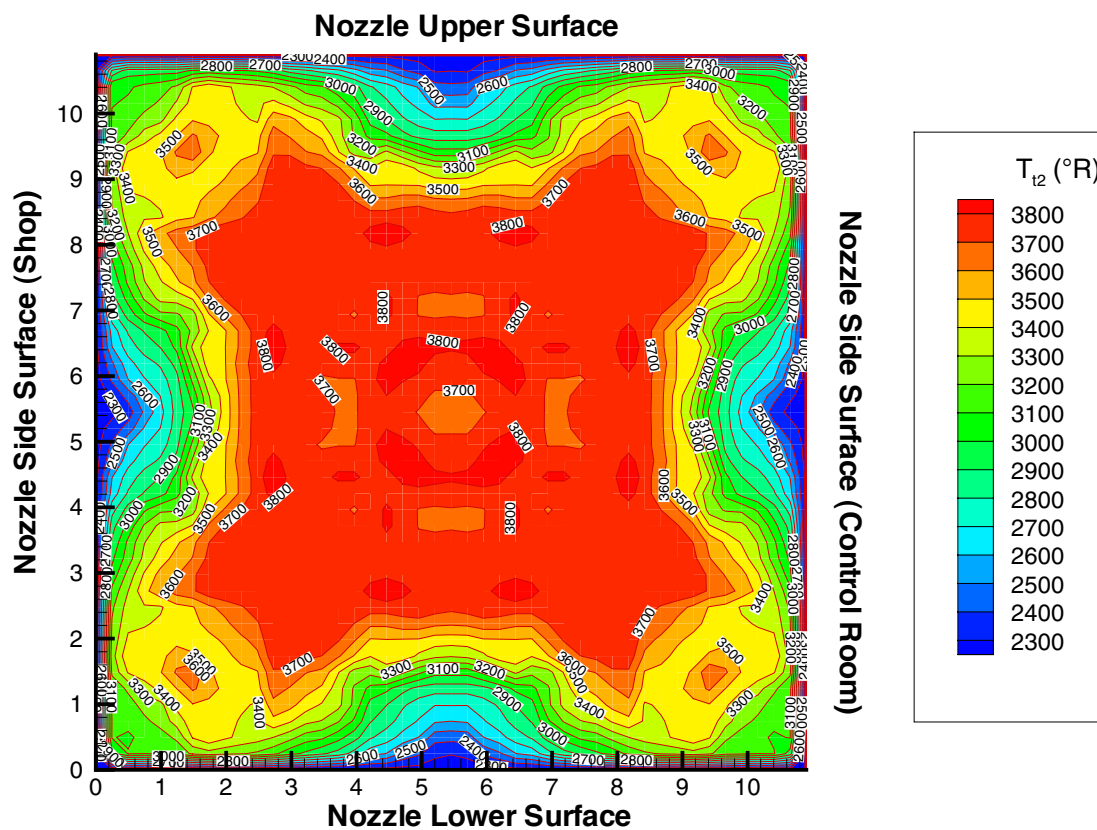


Figure 18e. 1986 total temperature contours (measured) at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

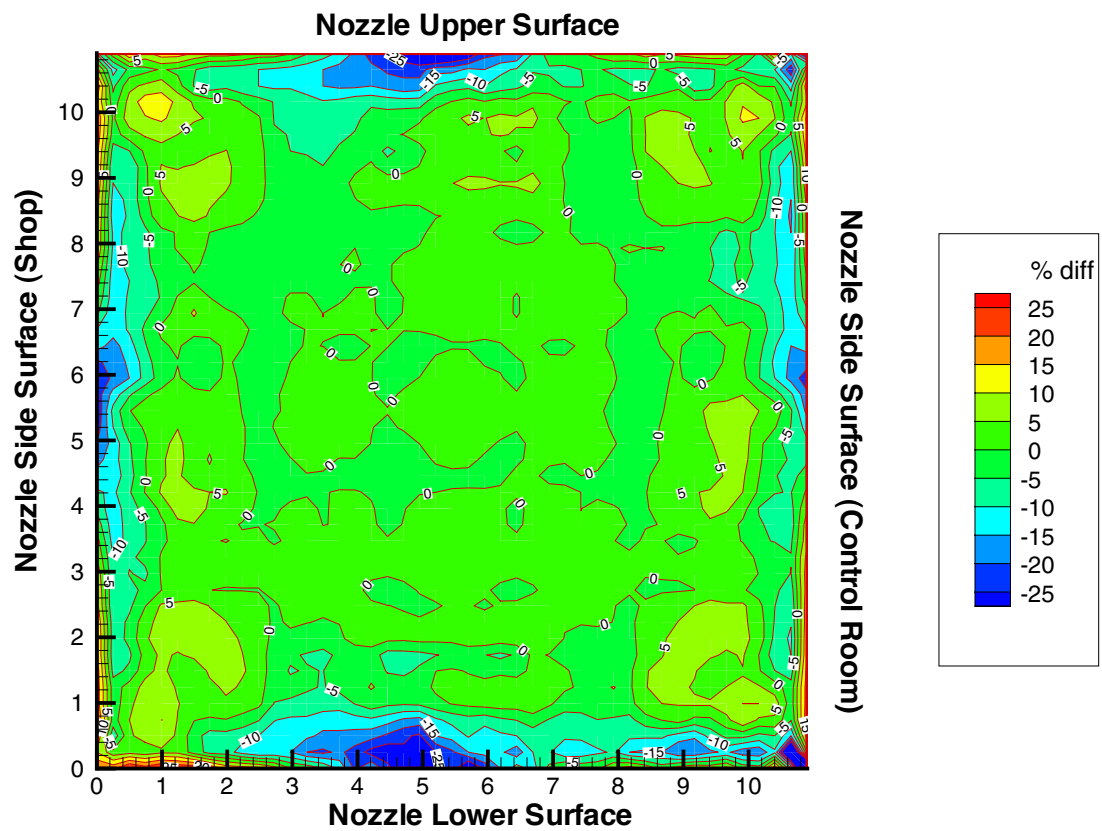


Figure 18f. 1986/1998 total temperature delta contours at the exit plane of the Mach 6 AHSTF nozzle: Mach 7 enthalpy test point (PT1 = 410 psia, HST = 1040 btu/lbm). All dimensions are in inches.

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14. ABSTRACT A calibration of the Arc-Heated Scramjet Test Facility (AHSTF) Mach 4.7 and Mach 6 nozzles was performed in 1998. For each nozzle, three different typical facility operating test points were selected for calibration. Each survey consisted of measurements, at 340 separate locations across the 11 inch square nozzle exit plane, of pitot pressure, static pressure, and total temperature. Measurement density was higher (4/inch) in the boundary layer near the nozzle wall than in the core nozzle flow (1/inch). The results generated for each of these calibration surveys were contour plots at the nozzle exit plane of the measured and calculated flow properties which completely defined the thermodynamic state of the nozzle exit flow. An area integration of the mass flux at the nozzle exit for each survey was compared to the AHSTF mass flow meter results to provide an indication of the overall quality of the calibration performed. The percent difference between the integrated nozzle exit mass flow and the flow meter ranged from 0.0 to 1.3 percent for the six surveys. Finally, a comparison of this 1998 calibration was made with the 1986 calibration. Differences of less than 10 percent were found within the nozzle core flow while in the boundary layer differences on the order of 20 percent were quite common.						
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